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Review

A Review of Carbon Emissions from Electrical Machine Materials

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Abstract: As the world embarks on a global mission to tackle climate change, reducing carbon represents a key challenge given the escalating global warming. The U.K. is among many other nations that are determined to decarbonise all sectors and strive to achieve a net zero carbon target by 2050. While much attention has been paid to improving performance and reducing carbon emissions in electrical machines, the current research landscape focuses mainly on the thermal and electromagnetic facets. Surprisingly, carbon emissions from the production stage, especially those related to raw material consumption, remain a largely unexplored area. This paper wishes to shed light on a neglected dimension by providing a comprehensive review of carbon emissions in the manufacture of electrical machines, thus contributing significantly to the wider discourse on carbon emission reduction by comparing the carbon emission values associated with various materials commonly used for the main components of these machines. A further case study is included to assess and explore the impact of material alterations on a synchronous machine, from a carbon emission perspective. A reliable material guide will provide engineers at the design stage with the critical insight needed to make informed material selection decisions, highlighting the critical role of carbon emission values beyond conventional thermal and electromagnetic considerations, achieving sustainable and environmentally conscious electrical machine design.

Keywords: electrical machines; carbon emission; materials; embedded carbon; primary production

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1. Introduction

Industries are actively reducing energy consumption and carbon emissions to meet the goal as part of the global drive towards environmental sustainability and improved energy efficiency. While electric generators produce practically all electric power globally, electric motors account for approximately 60% of the U.K. industrial electricity consumption [1]. In particular, electric motor drives are responsible for consuming approximately 43% to 46% of the world's electricity and emitting approximately 6040 million tonnes (Mt) of CO_2 annually [2]. These statistics underline the urgent need to optimise the performance of electric motors in the wider context of environmental protection and energy efficiency.

The increasing reliance on electrical machines in various sectors requires a comprehensive approach beyond the operational phase. Recognising these machines' critical role in contributing to environmental impacts during production is essential to achieving the integrated sustainability goals. Despite the central emphasis on efficiency improvements, the environmental impact of manufacturing processes needs to be addressed.

In particular, the carbon emissions associated with the primary manufacturing phase of electric motors and generators should be highlighted as being of paramount importance. The carbon emissions associated with raw materials represent a significant proportion, up to 90% of the total emissions during the manufacturing phase of electric machines [3]. Recognising this critical dimension is becoming an integral part of formulating effective carbon reduction strategies and promoting sustainable practices in electrical machine manufacturing processes.

This paper aims to provide a thorough investigation and a comprehensive overview of the carbon emissions associated with the materials commonly used to manufacture key components for electrical machines during primary production. Depending on the specific type of electrical machine, these components typically comprise a diverse range, including, but not limited to, the rotor core, stator, magnets, shaft, insulation, housing, end brackets, bearings, and various other integral parts.

This paper highlights the concept of the carbon emission factor, also known as the embodied carbon footprint of a material. This critical metric serves as a quantitative measure that accurately measures the amount of carbon released into the atmosphere during the production of a given material. Expressing this carbon emission factor in total greenhouse gas emissions, measured in kilograms of carbon dioxide equivalent per kilogram of material produced ($kgCO_2e/kg$), provides a standardised and insightful perspective.

By delving into the intricacies of the carbon emissions associated with the various materials used in manufacturing key electrical machine components, this paper aims to contribute valuable insights to the wider discourse on sustainable manufacturing practices. A careful examination of the carbon emission factor for each material is intended to provide engineers and industry stakeholders with the knowledge needed to make informed decisions during the design and manufacturing phases of electrical machines. Ultimately, this effort will promote more sustainable and environmentally conscious practices within the electrical machinery industry.

This paper is organised as follows. Section 2 of this paper explains the methodology used to analyse carbon emissions, while Sections 3 and 4 provide a comprehensive assessment and discussion of all machine component materials using the life cycle assessment (LCA) methodology. Active components such as the stator lamination, winding, and magnet are covered, as are passive components such as the housing, bearings, shaft, and insulation. A detailed case study is presented in Section 5, using a synchronous machine to investigate the impact of material changes from a carbon emissions perspective. Finally, Section 6 concludes the paper by summarising the key findings and providing an outlook for future exploration and research.

2. Carbon Emission Analysis

The main greenhouse gases (GHGs) in the atmosphere are carbon dioxide (CO_2), methane (CH_4), nitrous oxide (N_2O), fluorinated gases and water vapour. CO_2 is the most important GHG emitted by human activities regarding the amount released and the overall effect on global warming. Therefore, the term carbon dioxide equivalent, or CO_2e, is often used when referring to a collective number of GHGs and indicates the amount of CO_2 that would have the same global warming effect for each quantity and form of GHG, as CO_2 is considered to be the most important GHG [4].

Although there are many different natural sources of CO_2 emissions, since the Industrial Revolution, the amount of CO_2 in the atmosphere has increased due to human-related emissions [5]. In 2020, CO_2 accounted for approximately 79% of all human-induced GHG emissions in the United States, with the combustion and consumption of fossil fuels for transportation, power, and industrial processes accounting for the majority of CO_2 emissions from human activities, contributing 33%, 31%, and 16%, respectively [6].

2.1. Carbon Footprint at Multiple Scales

In order to assess the carbon footprint of an object, the existing literature provides three main methods: input–output analysis (IOA), life cycle analysis (LCA) and hybrid (IO-LCA), as shown in Figure 1 [7].

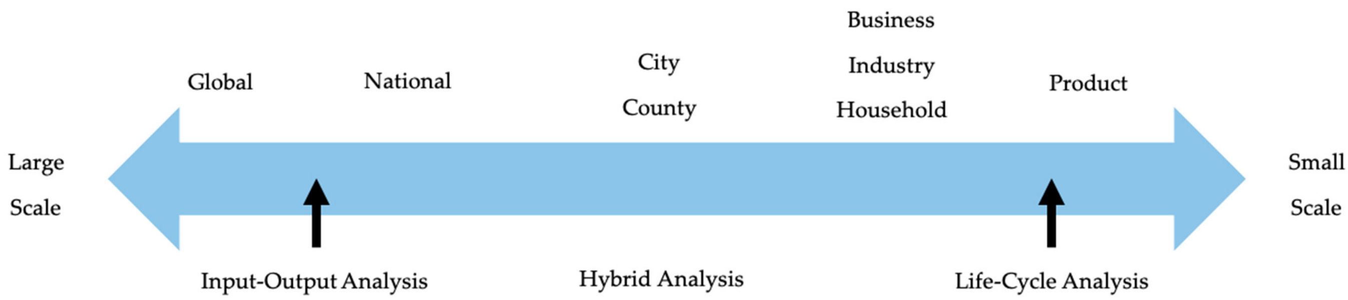

Figure 1. Carbon emission analysis methods.

The chosen method depends on the unit being analysed. The environmental impact associated with a product can be analysed with input–output analysis (IOA), given that it is caused directly and indirectly through a procedure or is compiled over the life stages. The product that has been analysed can be at the national level or for a sector-specific assessment [8].

Life cycle analysis (LCA) is an ISO-accredited carbon emission analysis method commonly used across industries to analyse the impact on the environment of consumer goods. It is especially widely used in analysing the carbon emission of building construction materials. This method was established with the life cycle inventory (LCI) to analyse the cumulative environmental impacts of products or processes through their life stages [9]. The hybrid method combines the advantages of the accurate process-based LCA and the comprehensiveness of IOA, which can be used to analyse products at all scales [10].

2.2. Life Cycle Analysis (LCA)

The life cycle analysis (LCA) approach for analysing environmental impacts is used extensively across various industries under the guideline ISO 14040 [11]. The main purpose of LCA is to identify the overall environmental impact throughout a product's lifetime, from raw material acquisition to disposal. The results gained from LCA can be utilised to identify and improve the environmental burden or integrate the decision-making stage by comparing the environmental impact of different products or processes [12]. With the ultimate goal of promoting environmental friendliness, industries are trying to achieve this either by reducing energy consumption or by using more sustainable materials. Based on the scale of electrical machines, carbon emissions of component materials can be analysed using the LCI technique. The LCA method has not been widely adopted in the electrical machinery industry when compared to the building and construction industry [13–15].

The LCA study can be divided into four phases, as shown in Figure 2 [16]: (1) goal and scope definition, where the study's intended purpose will be defined, as well as the system boundary and level of detail; (2) life cycle inventory (LCI) analysis, an inventory of environmental input and output data related to the system under investigation, which entails gathering data required from LCI to achieve the goal of the study; (3) life cycle impact assessment (LCIA), aims to support the LCI results, and to gain a better understanding of the environmental significance; and (4) interpretation, in which the findings of either or both LCI and LCIA are summarised and discussed as a foundation for conclusions in line with the goal and scope of the study [17].

In some circumstances, and this case, the objective of an LCA can be fulfilled by just an inventory analysis and an interpretation, excluding the LCIA phase, which can be described as an LCI study. Both the LCA studies and LCI studies are covered under the International Standard 14040. The LCI phase of LCA research should be distinct from LCI investigations [11].

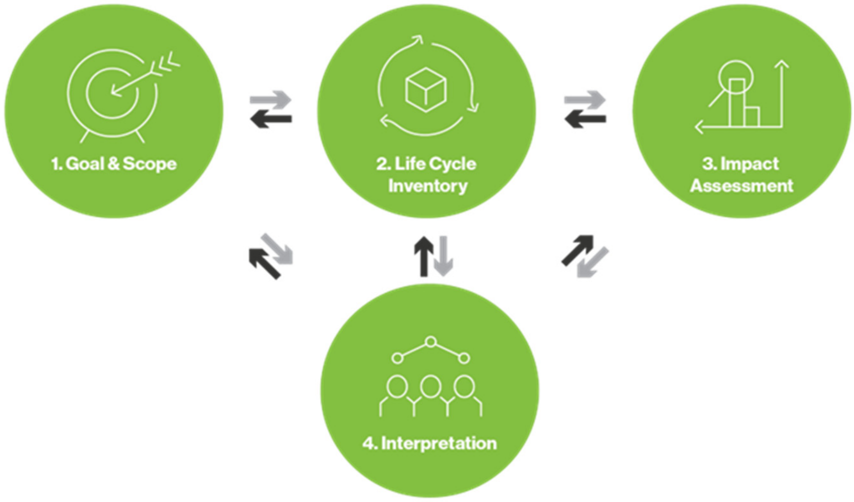

Figure 2. LCA life cycle stages.

The LCA technique shown in Figure 3 can be applied for various goals and scopes, such as cradle-to-grave, gate-to-gate, and cradle-to-factory gate analysis, through the typical stages of raw material extraction, materials manufacture, product manufacture, use stage and end-of-life.

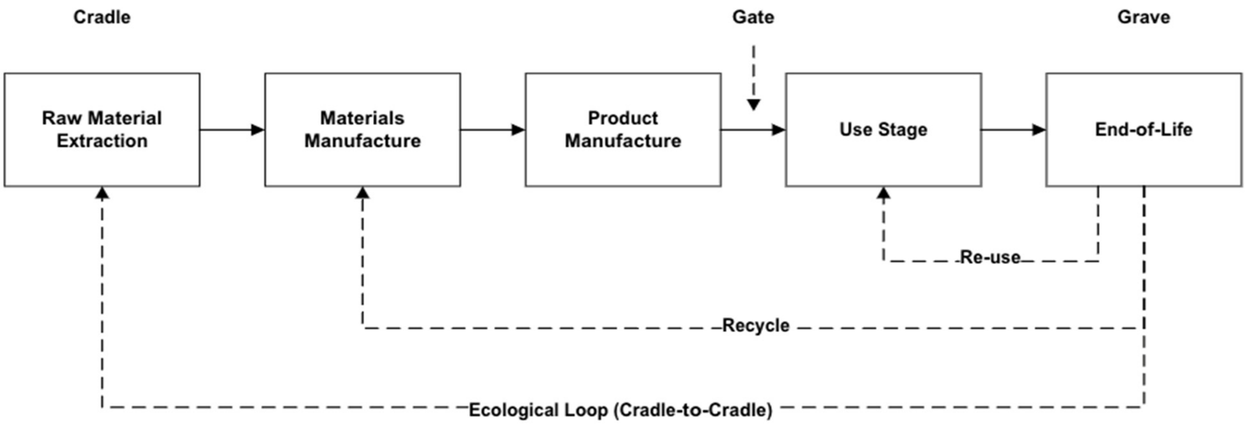

Figure 3. LCA technique.

The cradle-to-gate analysis focuses solely on the production stage of a product and represents the carbon impact from raw material to product manufacture to the moment it leaves the factory gate. For the building and construction industry, the cradle-to-gate approach is sometimes used as the basis for Environmental Product Declarations (EPDs) [18]. The cradle-to-grave analysis considers the impacts of all stages of a product's life cycle, from the extraction of raw materials to disposal. It represents the full life cycle assessment process from start to finish [19]. And cradle-to-cradle goes beyond the cradle-to-grave approach, as the materials and components of the product are designed to be reused or recycled indefinitely in an ecological cycle, minimising the overall environmental impact [20].

The life cycle inventory (LCI) was developed using a technique for studying the cumulative environmental effects throughout a product, process, or activity [21]. The LCA standard states that a material's overall environmental impact is determined as a multiple of the material's mass and the corresponding carbon emission factor obtained from LCI.

2.3. Life Cycle Inventory (LCI)

A life cycle inventory assesses a product's energy and raw material requirements, air emissions, water emissions, solid waste generation, and other outflows [21]. The inventory creates a database with the energy and materials utilised and the pollutants released into the environment, also known as carbon emission factors in $kgCO_2e/kg$.

The carbon emission factors are heavily influenced by energy consumption during the first stages of material production, such as mining. The energy efficiency and intensity of industrial processes in various countries and facilities within a country can vary by relatively considerable margins. There are four main factors that contribute to the different yet continuously changing energy intensity: the variation of raw materials such as ore and scrap, the mix of materials produced, the material losses during production, and the energy efficiency of the production facilities [22].

The primary production of a material listed in LCI generally utilises the cradle-to-gate approach, which includes the overall emission factor associated with the processes of raw material extraction, materials manufacture, and product manufacture.

Recourses such as Idemat, Inventory of Carbon and Energy (ICE), and Ecoinvent provide a detailed aspect of the ins and outflows of materials. Though readily available databases contain numerous information regarding generic materials, it can be difficult to locate and identify a specific material spread across many sources, especially the specific materials related to electrical machine components, as some do not exist in these readily available databases. Therefore, the research gap in carbon emission remains within the electrical machinery industry.

Due to varying production procedures, heating systems, and electrical energy sources, the data on carbon emission values may differ for the same material. It is also worth noting that the carbon emission factors presented are in default virgin/primary materials unless specified otherwise. Using the data-driven LCA technique, the carbon emission factors included in this paper were obtained from the life cycle inventory within the framework of the cradle-to-gate approach, which covers the production stages from the extraction of raw materials (cradle) to leaving the factories (gate). The decision to exclude the operational, end-of-life and recycling stages is a deliberate choice to maintain a focused examination of the primary production phase. The intention is to provide a detailed understanding of the initial carbon footprint associated with materials used in electrical machine components during extraction and processing.

3. Active Components

This section describes the associated carbon emission factors of commonly used materials for active e-machine components, including machine windings as well as hard and soft magnetic materials. Active components are essential elements in electrical machines that convert energy. The material used for the winding conducts electrical current and generates the magnetic field needed for the machine to operate. The magnetic materials that make up the core of the machine must be able to magnetise and demagnetise effectively to function properly. The selection of the appropriate core and winding materials for active components is a critical stage in the design of electrical machines, as the efficiency of the machine is closely related to the energy losses from these components.

3.1. Winding Materials

For alternating current (A.C.) induction and synchronous machines, windings essentially serve two functions: induce an electromotive force (EMF) and produce a rotating magneto-motive force (MMF). Possible materials used for wires are listed in Table 1.

Table 1. Carbon emission factors of commonly used winding materials.

Material	CO_2 Emission Factor $kgCO_2e/kg$	References
Copper	4.11, 5.40–8.00, 3.81	[23–26]
Aluminium	8.82, 9.16	[24,26]
Silver	123.70, 104.00	[24,27]

The range of 3.81 to 8 $kgCO_2e/kg$ signifies that comparatively, at a per unit mass level, copper has the least negative impact on the environment in terms of carbon emissions. Copper is the most widely used material in motor applications [28] with its excellent electrical conductivity and relatively low-price characteristics, though exhibiting problems such as higher mass density.

In contrast, silver is an excellent option for electrical and electronic applications where optimising conductivity is prioritised. Silver has several outstanding qualities, but several drawbacks prevent it from being widely used as a winding material in mass manufacturing.

With the first and most obvious flaw being its high price, as a result, the cost of producing electrical parts, machines, and devices on a wide scale would rise dramatically if silver were used as a winding material. Another important aspect that restricts silver's extensive use is its restricted supply. Supply limitations and price swings result from the fact that there are fewer silver reserves than there are geographically abundant and widely distributed copper reserves. This presents difficulties for industries looking for dependable and sustainable supply chains, particularly in high-volume manufacturing. Another issue with silver, especially in the context of this paper, is that it has a heavy impact on the environment. With values of 104 and 123.7 $kgCO_2e/kg$, silver production emits significantly (around 30 times) more carbon than the other electrically conductive materials.

Another material that is used for winding with increased mention/research in recent literature is aluminium. Although it has lower carbon emission values than silver, it nevertheless emits more carbon than copper on a per unit mass basis. Aluminium emits between 8.82 and 9.16 $kgCO_2e/kg$, which is up to 58% more carbon-intensive than copper. Aluminium also has several drawbacks when used as a winding material due to its lower conductivity and higher electrical resistance than copper. As a result of the higher heat losses caused by the increased resistance, the overall efficiency may be decreased. Larger motor designs and thicker wire diameters are required in order to produce the same power outputs as copper windings. To get a similar level of performance, motors wound with aluminium may need to occupy more space and may be bulkier than equivalent motors wound with copper. Despite these factors, there are some circumstances where employing aluminium wires may be beneficial. Aluminium, for example, can be favoured in applications where the weight or cost is a top concern.

3.2. Magnets

Hard and soft magnetic materials play a crucial role in electrical machines' design and performance, acting as the flux sources and critical magnetic circuit flux paths. To generate magnetic fields, permanent magnets (P.M.s) can be attached to the rotor in place of rotor windings. The common types of P.M.s in the market are neodymium–iron–boron (NdFeB), samarium–cobalt (SmCo), Alnico, and ceramic magnets.

Amongst the rare earth permanent magnets (REPMs), NdFeB is the most powerful magnet available on the market. Sintered neodymium magnets offer significantly higher coercivity than other permanent magnets and provide superior energy for their small size [29]. They come in various sizes, shapes, and grades and are also reasonably low-priced.

In terms of strength, SmCo magnets are close to their NdFeB counterparts but have superior temperature stability and coercivity [30]. They offer unique capabilities such as higher energy density at elevated temperatures, as high as 300 °C. Additionally, they exhibit exceptionally high corrosion and demagnetisation resistance.

Before the invention of rare earth magnets in the 1970s, alnico magnets were the strongest magnets that existed. Alnico is an iron alloy composed of aluminium, nickel, and cobalt, as well as iron and copper [31]. They can operate at high temperatures and have excellent temperature stability, while they are less coercive than other magnet materials and have a high magnetic remanence. They are physically less fragile than neodymium, samarium cobalt, and ceramic magnets [32].

Ferrite or ceramic magnets are currently the least expensive hard magnets. Ceramic magnets can be utilised at relatively high temperatures and have a medium magnetic strength since they are composed of strontium carbonate and iron oxide [33].

The carbon emission factors of the aforementioned virgin P.M.s are listed in Figure 4. The presented values include the carbon emission from rare earth elements (REEs) mining to magnet production. Currently, there is not much information on the carbon footprints of alnico magnets. The value presented in the figure below is an estimation based on the composition of the magnets (Alnico 5—Al 8%, Ni 14%, Co 24%, Cu 3%, Fe 51%). It is safe to conclude that due to the numerous production processes of REPMs, the carbon footprint of non-rare earth magnets is significantly lower than that of REPMs per kilogramme of material.

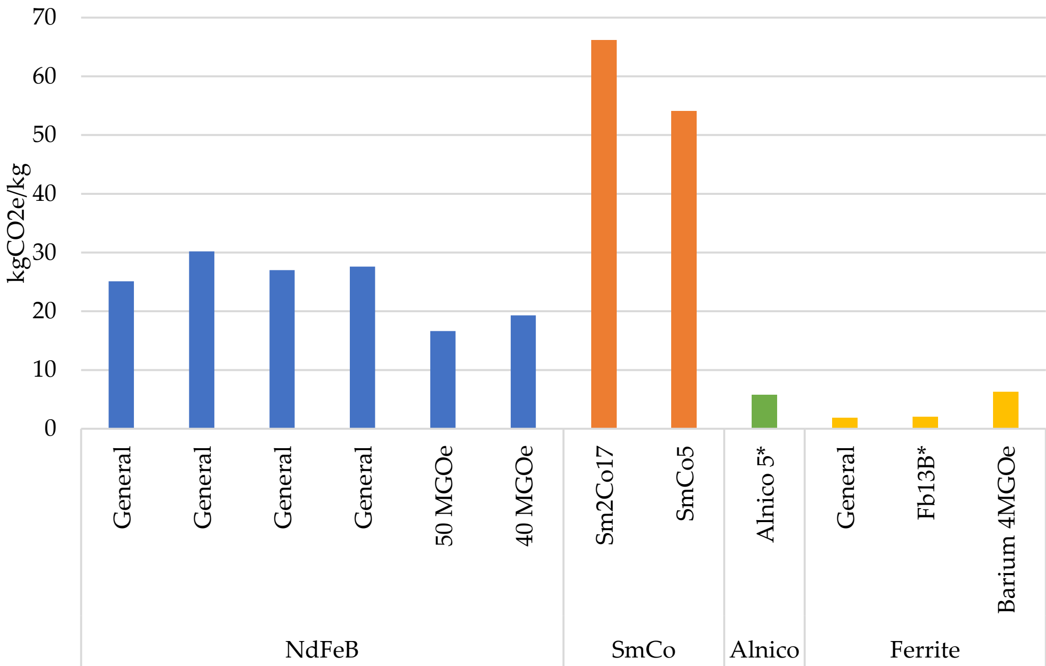

Figure 4. Carbon emission factors of commonly used magnets. * Carbon emission factors are calculated based on the material compositions.

Alnico and ferrite magnets have a carbon emission factor of 5.7 and 1.9 to 6.3 kgCO_2e/kg, respectively [24–26]. This is relatively low compared to the carbon emission factor of NdFeB magnets, which ranges from 16.6 to 30.2 kgCO_2e/kg [24,34–36], and up to 66.2 kgCO_2e/kg for SmCo magnets [24,34]. In the modern world, rare earth magnets are popular mainly because of their higher magnetic properties at room temperature, reduced material costs, and improved corrosion resistance [37]. A REPM has 2–7 times the strength of a regular magnet in terms of power [38] and the carbon footprint of alnico or ferrite magnets. Based on the data collected, general SmCo could be up to 30 times more carbon-intensive than general ferrite magnets.

When magnets derived from virgin raw materials and recycled magnets are compared, the results show that the recycled ones have significantly fewer adverse environmental effects than the production of virgin magnets. At the same time, the recycled magnets can also have stronger magnetic properties and superior microstructure [36]. The carbon footprint from recycled magnets is halved with respect to the virgin magnets for NdFeB magnets. In Europe, less than 1% of the rare earth permanent magnet scrap has been recovered, which provides a tremendous potential resource with a low carbon footprint [39].

3.3. Lamination

The most commonly used soft magnetic core materials for laminations are silicon steels. The silicon content in electrical steel is usually between 1.5% and 3.5%, whereas oriented silicon steel contains a higher silicon content than non-oriented, around 3–3.5%.

Nickel alloy is an alternate material with high permeability and is used when minimal core losses are required at high frequencies. However, it costs significantly more than silicon steel and requires meticulous annealing to attain the necessary characteristics and maintain quality.

When the use of high saturation flux density and power-to-weight ratio (kW/kg) is prioritised, such as in aerospace applications, a cobalt–iron (CoFe) alloy can be used for the laminations.

Figure 5 shows the associated carbon emission factors for lamination materials. Since only information on the individual composition of the materials was available from the LCI, some of the values shown were calculated using the typical composition percentages of the lamination materials. Hence, they can be treated as approximations.

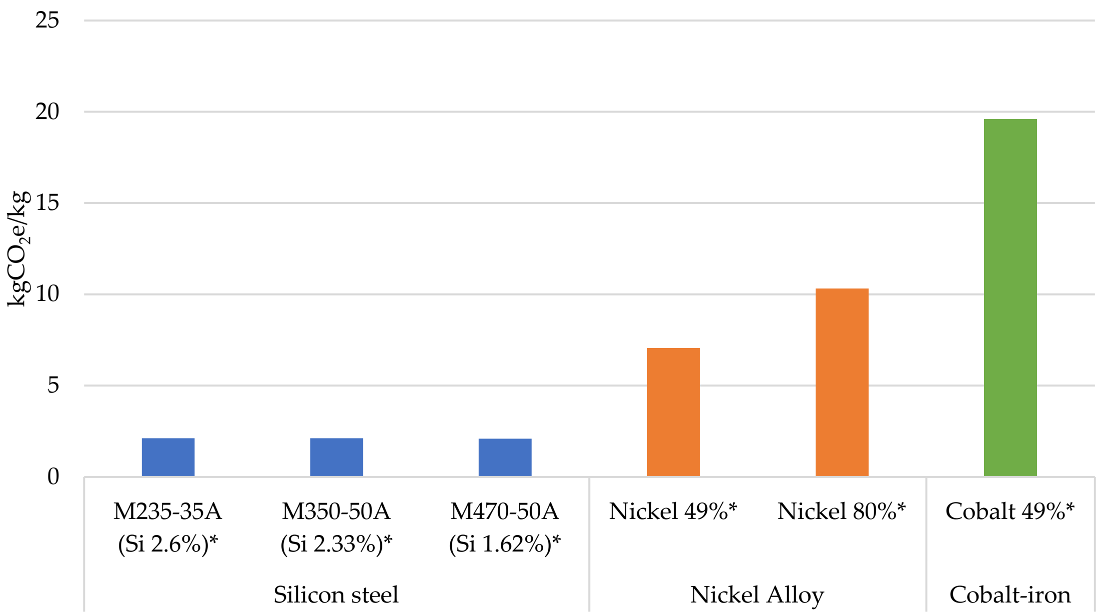

Figure 5. Carbon emission factors of commonly used lamination materials. * Carbon emission factors are calculated based on the material compositions.

The most popular material, silicon steel, has comparatively low carbon emission factors of around 2 kgCO_2e/kg [24,26,40]. It is noteworthy that the silicon concentration of the material has an impact on the emission values, where higher silicon content correlates with higher total emission values.

The emission value of a nickel alloy containing 49% nickel is roughly 7.05 kgCO_2e/kg, while an alloy containing 80% nickel has a higher emission value of around 10.3 kgCO_2e/kg [26,41,42].

High performance 49% cobalt iron stands out among the studied materials as having the highest emission value of about 19.59 kgCO_2e/kg [26,43]. Due to its high saturation flux density, cobalt laminations offer special advantages in several high-performance applications. Alternative materials might be used in applications where the special advantages of cobalt are not required due to its higher cost and environmental considerations. Therefore, cobalt-containing materials should be used cautiously since they can negatively impact the environment during production and should be assessed in light of sustainability objectives.

4. Passive Components

Following the section on active components, electrical machines' passive components will be reviewed in this section, including the housing, end brackets, shaft, bearings, wire insulation, machine insulation systems, impregnation, and encapsulation. As with the passive components, the main considerations here are the physical and structural properties of the materials. Therefore, in the basic principle of carbon emission of materials, the total emission value of a material is always increased when both variables—its mass and its carbon emission factor—are large; conversely, lower values of both variables result in lower emissions. Calculating the total carbon emission value of the passive component with different material qualities is crucial for a fair comparison.

4.1. Housing and End Brackets

The machine housing is a crucial component designed to support and protect machine components from external substances in various environmental settings. Numerous materials and production processes can be used for motor housing manufacturing.

Due to its high machinability, as well as strong, durable, lightweight, and recyclable characteristics, aluminium alloy is the most widely used material for the machine housing.

Cast iron housings are typically employed instead of aluminium for heavy-duty and large-size electric machines as they offer the necessary strength and hardness. There are four main and distinct varieties of cast iron, gray, white, ductile, and malleable cast iron, each with a unique carbon structure that delivers a unique microstructure and mechanical characteristics. Gray cast iron is the most commonly used cast iron, comprising 2.5–4% carbon and 1–3% silicon. Gray cast iron exhibits the characteristics of high stiffness and thermal conductivity, vibration dampening, and machinability [44]. When a higher strength and ductility are required, ductile cast iron with a composition of 3–4% carbon and 1.8–2.8% silicon may be employed instead of gray iron, as ductile iron is more durable, reliable, and tough [45].

Steel casting can be used for housings that demand high strength and shock resistance, which cast iron cannot provide. Cast steel can be split into carbon-cast steel and alloyed-cast steel. Carbon steel casting can be further divided according to its carbon content to obtain different strength varieties. Alloy steel castings can be divided into low- or high-alloy. Low-alloy cast steel contains less than 8% alloy content that behaves comparably to regular carbon steel but has increased hardenability. High-alloy cast steel has an alloy composition of more than 8% and is designed to create particular properties such as corrosion, heat, and wear resistance. Stainless steel with more than 10.5% chromium is the most commonly used high-alloy steel [46]. Stainless steel has excellent corrosion resistance due to the addition of chromium, which generates a passivation layer of chromium oxide when exposed to oxygen. However, high-alloy cast steel is rarely employed as machine components unless cast iron is unable to meet the requirement for high strength or anticorrosion.

Figure 6 below presents the carbon emission factors of the aforementioned housing materials. It can be seen from the graph that various forms of aluminium have the highest values of carbon emission, with values ranging from 8.82 to 13.1 kgCO_2e/kg [24,26,47,48]. It is followed by stainless steel, with emission values ranging from 4.7 to 6.2 kgCO_2e/kg [24,26,40]. Cast iron shows slightly higher emission values with 0.97 to 3.41 kgCO_2e/kg [24,47,48], compared to those of carbon steel of 0.98 to 2.8 kgCO_2e/kg [24,47,48].

Although aluminium has the highest carbon emission factors, it also has the lowest mass density among all the materials considered, with an average density of approximately 2.7 g/cm^3. In comparison, cast iron has a density of around 6.8–7.8 g/cm^3, carbon steel of 7.8 g/cm^3, and stainless steel of around 7.4–8 g/cm^3 [49]. This difference in density can have a significant impact on the overall weight and size of the components created from these materials.

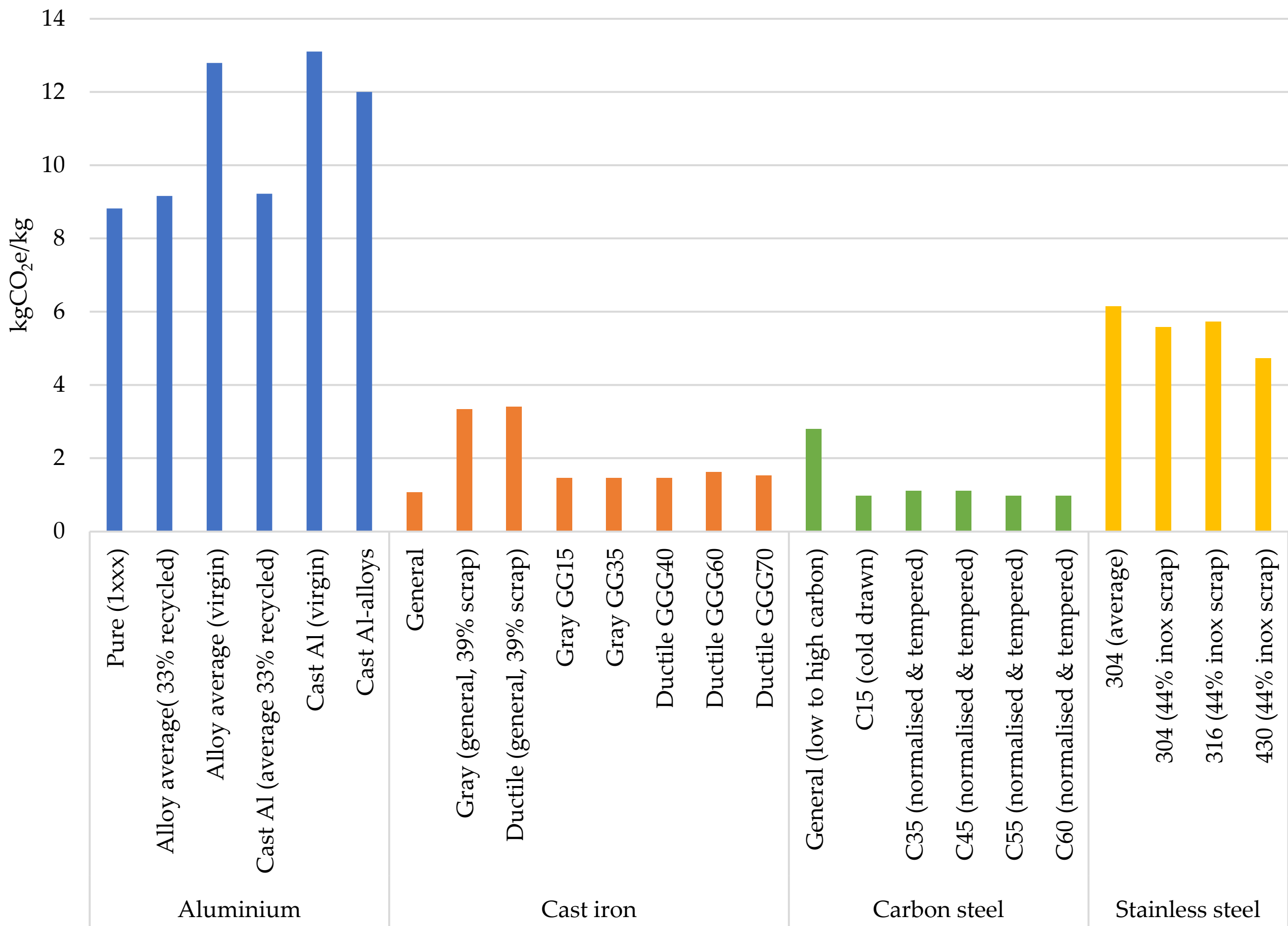

Figure 6. Carbon emission factors of commonly used machine housing materials.

Similar to machine housings, end brackets play a crucial role in electrical machines. They act as the end covers of the frame, protecting the internal active and passive components while supporting the bearings and facilitating cooling paths. End brackets are often cast and are commonly also created from the materials listed in Figure 6.

In summary, aluminium has the highest carbon emission factors, yet the lowest density of the materials listed, making it suitable for lightweight applications where weight reduction is essential. On the other hand, cast iron, with slightly higher carbon emission values, is preferred for applications where higher strength, rigidity and vibration damping are critical. For fixed-volume enclosures, cast iron will be heavier but will have a lower carbon emission per component compared to aluminium. In contrast, aluminium will be much lighter but have a higher carbon emission value. The choice between aluminium alloys and cast iron for the manufacture of end brackets ultimately depends on the balance between the specific requirements of the machine and the desired environmental and performance objectives.

4.2. Wire Insulation

Magnet wires such as copper or aluminium are generally coated with one or multiple layers of polymer film insulation to attain a durable, consistent insulating layer. It is usually necessary to use several compositions to achieve the best insulation results with multilayer coatings.

Different types of wire insulation can be incorporated with magnet wires with different thermal class ranges. The most commonly used insulation and their temperature ratings are Polyurethane (P.U.) at 155–180 °C, Polyetherimide (PEI) at 180–200 °C, Polyamide-imide (PAI) at 220 °C, and aramid (aromatic polyimide, P.I.) at 240 °C [50,51]. Recent technologies discovered that Polyetheretherketone (PEEK)-coated wire can achieve up to 260 °C [52].

Only applications with low temperatures up to 105 °C can employ organic insulation materials such as cotton, paper, or silk. It is difficult for conventional polymer-based insulation to operate in high-performance machines well above 260 °C. Recent studies have shown that inorganic insulation materials such as glass-coated, ceramic-coated, and glass-fibre-insulated wire can be employed in high-performance machines that operate at temperatures up to 500–600 °C [53].

The commonly used wire insulation materials and their associated carbon emission factors are shown in Figure 7.

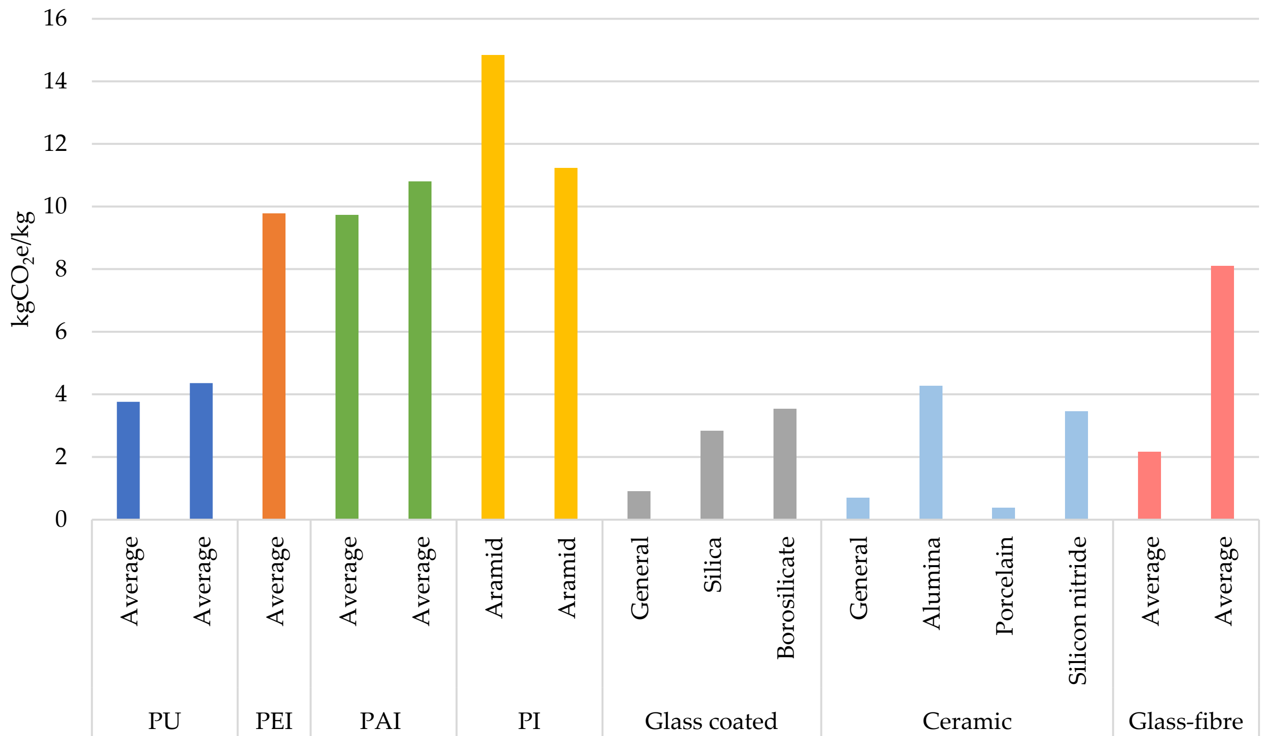

Figure 7. Carbon emission factors of commonly used wire insulation materials.

The carbon emission factors associated with different magnet wire insulation materials vary significantly, offering a range of environmental impacts. With values ranging from 0.37 to 4.27 $kgCO_2e/kg$ and 0.91 to 3.53 $kgCO_2e/kg$ [24,26], respectively, depending on the type of the inorganic insulation material, ceramic and glass-coated insulations for extreme temperatures stand out as having the lowest carbon emission factors among these materials.

The highest carbon emission factor is found for P.I. (polyimide) insulation with values of 11.24 and 14.84 $kgCO_2e/kg$ [24,54]. This is followed by PEI and PAI with average emission factors of 9.77 $kgCO_2e/kg$ [24], and 9.73 to 10.8 $kgCO_2e/kg$ [55], respectively.

The carbon emission factor of P.U. insulation averages between 3.76 and 4.36 $kgCO_2e/kg$ [26], making it a mid-range option in terms of environmental impact. Glass-fibre insulation, another commonly used material, exhibits emission values of 2.16 and 8.1 $kgCO_2e/kg$ [24,26].

A clear pattern observed in the data is that, among thermoplastics, there is a direct correlation between temperature tolerance and carbon emission factor. As the temperature tolerance of the insulation material increases (155–240 °C), so does its carbon emission factor. In contrast, inorganic insulation materials like glass-coated, ceramic-coated, and glass-fibre insulations demonstrate much lower average carbon emission factors compared to thermoplastics. Remarkably, these inorganic materials also exhibit exceptional temperature withstand capabilities, ranging from 500 °C to 600 °C.

There are trade-offs between performance, thermal characteristics, mechanical strength, and environmental impact when choosing the insulation material for magnet wire. While some materials have better electrical qualities or can tolerate high temperatures, they also produce more carbon emissions during manufacturing and production.

4.3. Insulation Systems

The magnet wire insulating varnish typically meets the requirement of turn-to-turn insulation for lower-power, low-voltage machines. Nevertheless, additional insulation may be necessary as the requirement increases, such as by wrapping magnet wires with glass fibre-reinforced mica tape before impregnated them with low-viscosity epoxy resin and curing at high temperatures [28].

Apart from magnet wire insulation, additional electrical insulation is needed wherever there is a difference in electric potential between two electric conductors. Stators can be insulated using various techniques, including over-moulding with thermoplastics, powder coating, and aramid or mylar layered paper.

Slot liners are the primary insulation component in an electrical machine; they act as an electrical insulation barrier between the winding and the lamination for both the stator and rotor and provide turn-to-ground insulations [56]. Therefore, they make up the majority of the machine's insulation systems. Insulation materials such as meta-aramid-based Nomex paper and polyimide-based Kapton film, or thermoplastic-based materials that are heat-resistant and mechanically stable, are typically used as slot liners and slot wedges.

In addition to the insulation mentioned earlier, powder coating is another technique that may be employed to insulate the stator and rotor. Materials such as epoxy, Glyptal, and Loctite can be used for a protective finish on the electrical components. This results in consistent insulation coating layers on the slot surfaces and partially on the stator and end surfaces. Due to its exceptional longevity and dielectric strength, epoxy powder coating has been effectively employed as a dielectric insulator on magnet wires.

Table 2 provides a list of the insulation materials and their associated carbon emission factors previously mentioned. It is important to note that some specific insulation materials, such as Nomex and Kapton, do not have direct carbon emission data available. In such cases, their main constituent materials, aramid, and polyimide, respectively, are listed instead. These values should be considered as relative approximations based on the known carbon emissions of the primary materials used in the insulation. Additionally, the emission factor value provided for Glyptal is also an estimation derived from available data on the material's primary composition, which includes ethylene glycol and phthalic acid.

Table 2. Carbon emission factors of commonly used insulation materials.

Material	CO_2 Emission Factor $kgCO_2e/kg$	References
Aramid	14.84, 11.24	[24,54]
Polyimide (PA6/66)	6.70/6.40, 9.47/7.92	[24,26]
Mica	2.40	[24]
Epoxy	2.24, 2.54–8.10	[24,54]
Glyptal (Ethylene glycol & Phthalic acid) *	1.95	[24]

* Carbon emission factors are calculated based on the material compositions.

The table shows the carbon emission factors of various insulation materials used in electrical applications. Glyptal stands out with the lowest carbon emission factor of 1.95 kgCO_2e/kg [24], making it an environmentally friendly option. Mica follows closely with an emission factor of 2.4 kgCO_2e/kg [24], demonstrating its relatively low environmental impact. Epoxy exhibits a wider range of emission factors, varying from 2.24 to 8.1 kgCO_2e/kg [24,54]. While the lower end of this range suggests a relatively eco-friendly choice, the higher end indicates a more considerable carbon footprint associated with certain variants.

Polyimide-based Kapton film falls within a range, averaging from 6.4 to 9.47 kgCO_2e/kg [24,26]. This places it in the mid-range in terms of carbon emissions among the listed materials. Aramid-based Nomex paper is shown to have the highest emission factors among the insulation materials, 11.24 and 14.84 kgCO_2e/kg [24,54]. This indicates that Nomex paper has a more substantial environmental impact compared to the other insulation materials listed.

4.4. Impregnation and Encapsulation

In electrical machines, bare windings tend to vibrate and bend, leading to early failures. To minimise vibration that might occur during operation, machine windings are typically treated with a resin such as epoxy or varnish [57]. Impregnation decreases air gaps and spaces between the coils, increasing the coils' average thermal conductivity. The process is usually completed with a Vacuum Pressure Impregnation (VPI) cycle, which can greatly minimise space, resulting in improved efficiency and a lower temperature difference in the windings.

Similar to impregnation, encapsulation is the complete encasement by epoxy or varnish of higher viscosity onto the windings. The resin typically creates a thicker and more complete coating than impregnation, with two or more cycles of VPI [58]. Encapsulation can be applied partially, such as to the end winding or entirely to the whole assembly for better and more durable protection.

The materials used for both processes usually have high dielectric strengths and high thermal conductivity. In addition to epoxy, other thermosets, such as phenolics and thermoset polyesters, have long been used as encapsulation materials for electrical machines. Thermoplastics have gained popularity in recent years as encapsulation materials due to their superior physical characteristics in narrow spaces compared to thermosets and eliminating the environmentally harmful solvent emissions from the volatile organic compounds used in thermoset impregnation. Commonly used thermoplastic encapsulation materials include Polyoxymethylene (acetals, POM), Polyamides(nylons, P.A.), Polyethylene terephthalate (PET), Polybutylene terephthalate (PBT), as well as glass fibre-reinforced thermoplastics. The aforementioned impregnation and encapsulation materials are shown in Figure 8 with their associated carbon emission factors.

The carbon emission factors of various thermoplastic insulation materials used in electrical applications vary significantly. Among them, PA6/66, and PA6/66 with 30% glass filled show the highest emission factors, ranging from 6.4 to 9.47 kgCO_2e/kg [24,26], and 5.13 to 8.04 kgCO_2e/kg [24], respectively.

On the other hand, materials such as PBT, phenolics, and PET have lower carbon emission factors of 1.63 kgCO_2e/kg, 1.81 kgCO_2e/kg, and 2.19 to 2.57 kgCO_2e/kg [24,25], respectively. In total, 30% glass-filled PET and epoxy fall within emission values of 2.18 and 3.4 kgCO_2e/kg [24] and 2.24 and 8.1 kgCO_2e/kg [24,54], respectively. Furthermore, polyester shows emission of 2.59 and 4.6 kgCO_2e/kg [24,25], while acetal has an emission value of 3.2 kgCO_2e/kg [24].

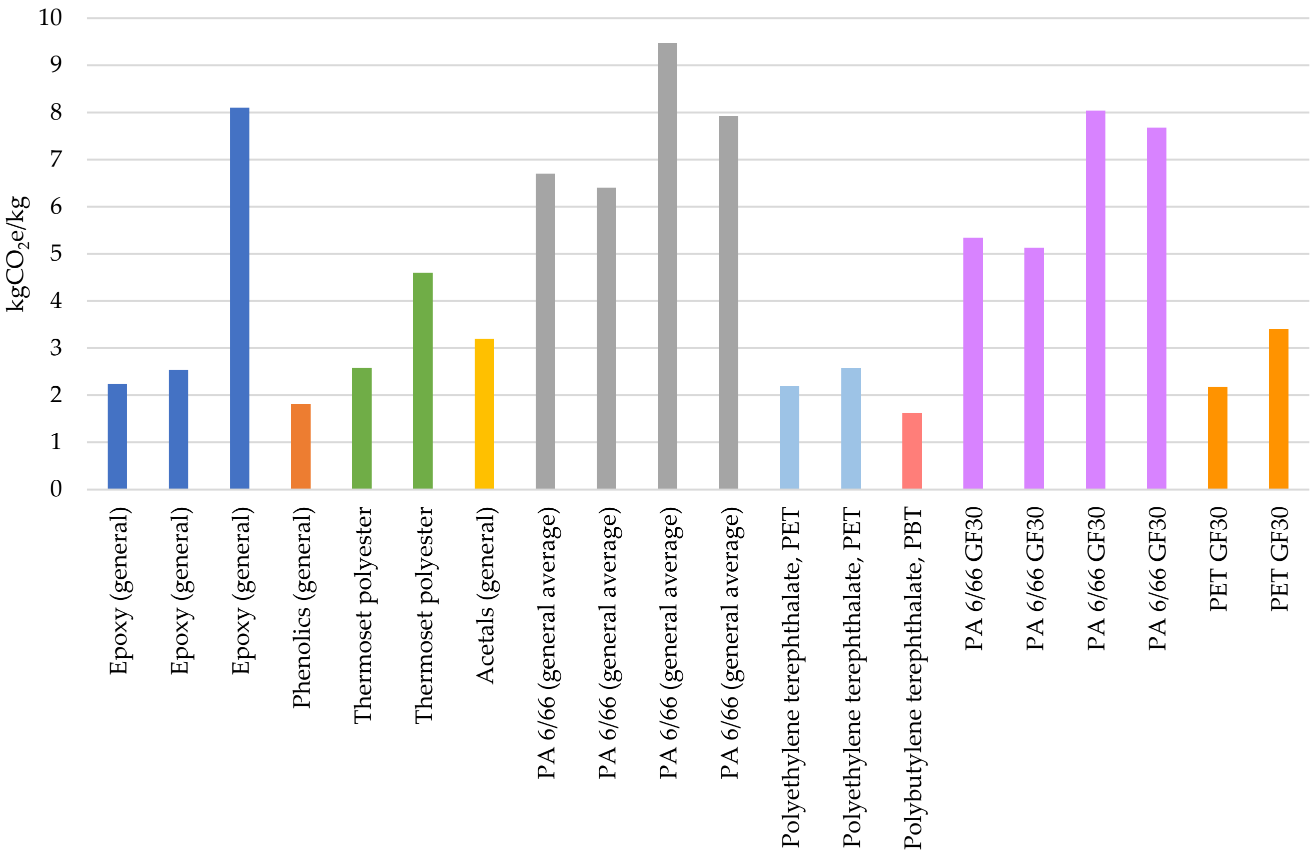

Figure 8. Carbon emission factors of commonly used impregnation and encapsulation materials.

4.5. Shaft

An electrical machine uses its shaft to provide torque and power to an external loading system. Shafts frequently experience a variety of coupled loads during operation, including torsion, bending, compression, and tension. They are designed primarily for maximum stiffness, rigidity, and minimum deflection to maintain shaft stress/strain below acceptable limits under various loading and operating situations.

Material selection for a shaft is crucial for ensuring the machine's regular and safe operation. Depending on the application's purposes, the shaft can be formed of ferrous, non-ferrous, or non-metal materials. Carbon steel, stainless steel, cast iron, and aluminium alloys are a few of the materials used to create shafts [59]. The criteria for choosing a shaft material are mainly based on its stiffness, wear resistance, machinability, and mechanical properties.

Carbon steel is the most popular shaft material, whereas the amount of carbon contents within the material can alter the mechanical and thermal properties. The metal has the same properties as iron, soft but easily formed with low carbon content. The hardness, yield, and tensile strength can also be increased by raising carbon contents. However, excessive carbon content can also make a material more brittle and impair its machining and welding capability [28]. Typical compositions of carbon can be categorised into three types: mild steel contains up to 0.3% of carbon, medium carbon steel 0.3% to 0.6%, and high-carbon steel 0.6–1.4% [60]. Most machine shafts are composed of medium carbon steel containing 0.2% to 0.5% carbon [28].

With a minimum chromium (Cr) content of 10.5%, stainless steel is one of the most resilient metals to use in corrosive environments. The metal's surface is protected by an invisible, corrosion-resistant passive layer of chromium oxide, formed naturally by combining chromium and moisture in the air [59]. Nickel (Ni) can be added to stainless steel to increase corrosion resistance. However, due to the heat produced during the machining process and challenges with chip breakage, stainless steel is more challenging to process than carbon steel [61].

Cast iron has good castability, low-notch sensitivity, low elastic modulus, high thermal conductivity, moderate resistance to thermal shock, and excellent vibration-damping qualities [28]. Since gray cast iron has a shear strength significantly higher than the tensile strength of other ferrous materials; it can tolerate more excellent shear tensile than tensile forces [10]. Yet, cast iron shafts are still uncommon in electrical machines.

Instead of steel, advanced high-tensile aluminium alloys, such as those strengthened with scandium and titanium, are used nowadays, especially in the automotive industry, as they are advantageous due to their high strength-to-density ratio and good machinability, whilst being prone to corrosive environments [28]. For the motor industry, aluminium shafts are only used in smaller, lower-torque machines.

Figure 6 provides detailed data on the carbon emission factors for these commonly used shaft materials. Among the materials, carbon steel stands out as the most frequently employed shaft material due to its favourable properties and relatively low environmental impact. Carbon steel has the lowest carbon emission value, ranging from 0.98 to 2.8 $kgCO_2e/kg$, making it an attractive option for many applications.

Cast iron follows closely with emissions ranging from 0.97 to 3.34 $kgCO_2e/kg$.

Aluminium, on the other hand, has the highest carbon footprint of the listed materials, ranging from 8.82 to 13.1 $kgCO_2e/kg$.

The choice of shaft material ultimately depends on several factors, including mechanical/rotor-dynamic requirements, environmental impact, cost considerations and specific application requirements. Engineers must weigh the trade-offs between material properties and environmental considerations to make informed decisions that meet sustainability goals and performance requirements.

4.6. Bearings

Bearings are critical features for electrical machines to ensure safe and smooth operation between the rotating and stationary components at high speeds while carrying the loads and reducing friction [62]. As a result, bearings are significantly impacted by heavy loads, necessitating a minimum hardness of 58 Rockwell for steel and 78–81 Rockwell for ceramic bearings.

For general applications that require high-strain strength and high wear resistance, metallic material chrome steel SAE 52100 has been widely used for roller, ball, and tapered roller bearings. Stainless steel AISI 440C may be used if the machine requires excellent corrosion resistance. It has a greater chromium concentration of up to 18% and is, therefore, suited for operating in harsh environments. AISI 440C has a lower hardness, an overall load-carrying capacity 20% lower than SAE 52100, and a higher production cost [28,63]. Other metallic materials used for bearings include copper–lead alloys, aluminium alloys, cast iron, bronze, and silver.

Non-metallic metals have also been commonly used for bearings, providing differentiated features that can be applied in various applications. Due to their lower heat conductivity than metallic materials, non-metallic materials are used in low-pressure-velocity (P.V.) value applications. Non-metallic materials can be classified into plastics, ceramics, and rubber. Figure 9 provides typical materials used for bearings and their carbon emission factor.

With values ranging from 8.8 to 13.1 $kgCO_2e/kg$ [24,26,47,48], aluminium has the greatest average carbon emission factor among the metallic materials studied. Following behind are bronze, copper-lead alloys, and stainless steel with emission values of 5.36 $kgCO_2e/kg$ [24], 3.56 and 4.9 $kgCO_2e/kg$ [24], and 4.69 $kgCO_2e/kg$ [24,26,40], respectively. Contrarily, chrome steel and cast iron have relatively low carbon emissions compared to the other metallic materials, with 2.1 $kgCO_2e/kg$ [24,26] and 0.97 to 3.41 $kgCO_2e/kg$ [47,48,64], respectively.

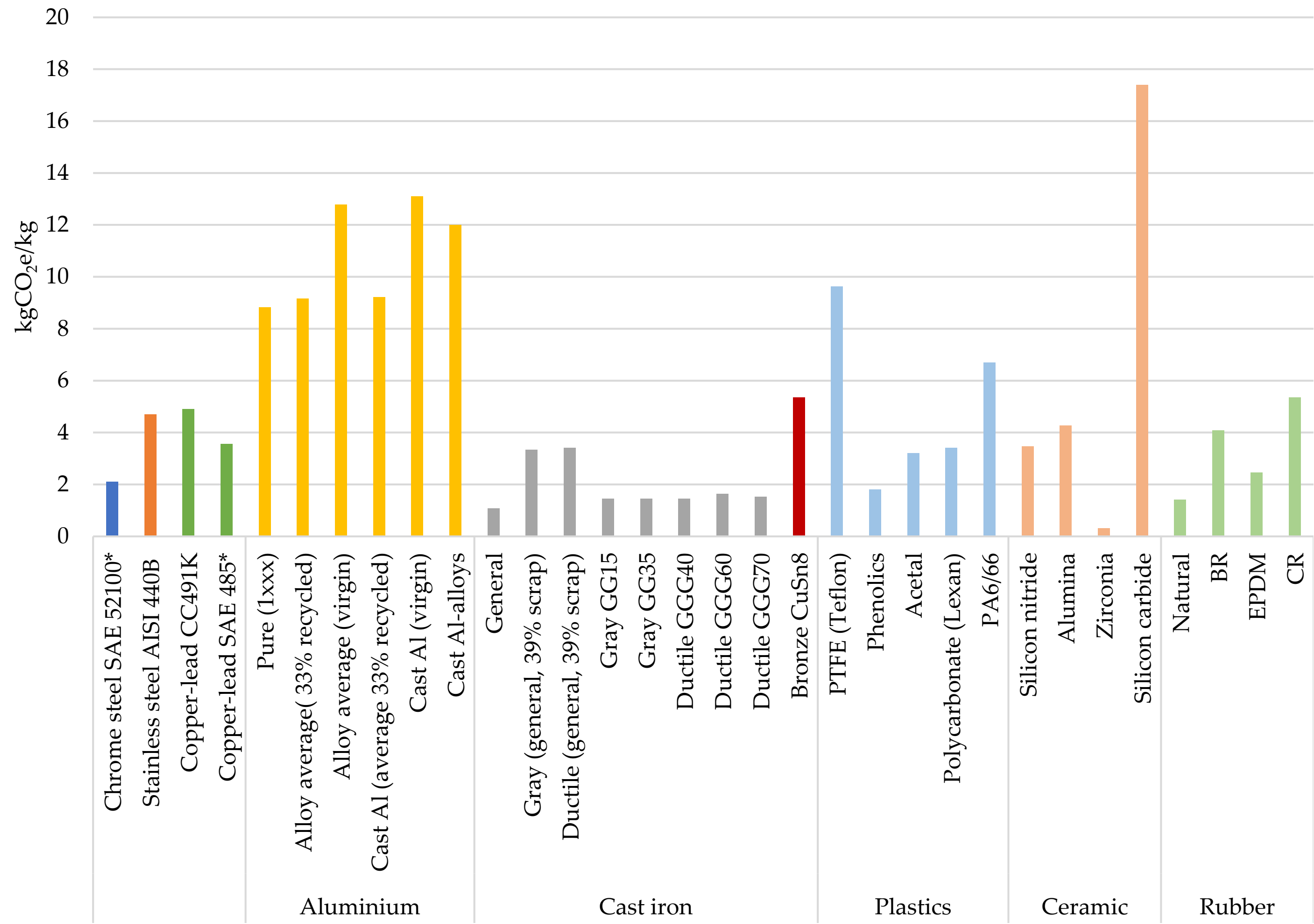

Figure 9. Carbon emission factors of commonly used bearing materials. * Carbon emission factors are calculated based on the material compositions.

The average emission values for the materials classified as plastics, ceramics, and rubber are similar and range from 1.81 to 9.62 $kgCO_2e/kg$, 0.32 to 17.4 $kgCO_2e/kg$, and 1.41 to 5.35 $kgCO_2e/kg$ [24], respectively.

5. Case Study

Following the principles of life cycle assessment (LCA), this section presents the carbon emissions associated with the components, starting from the acquisition of raw materials for a baseline machine. As a result, the content of this section also represents a detailed study of the various strategies aimed at reducing the carbon emissions of the basic components of the same baseline machine.

Systematically evaluating these results provides valuable insights into the most promising ways to improve the machine's environmental impact.

5.1. Carbon Emission Analysis of the Baseline Machine

The benchmark machine used for this case study is a 4-pole wound-field synchronous machine rated at an output power of 40 kW, and a speed of 1500 RPM. The machine is built on a frame that holds the stationary components of the main stator, while the rotating components of the main rotor, exciter rotor, and fan are all attached to a shaft and supported at both ends of the machine with bearings. Figures 10 and 11 show typical rotational and stationary components of synchronous machines, respectively. The mass and carbon emission comparison of various materials per component is shown in Table 3.

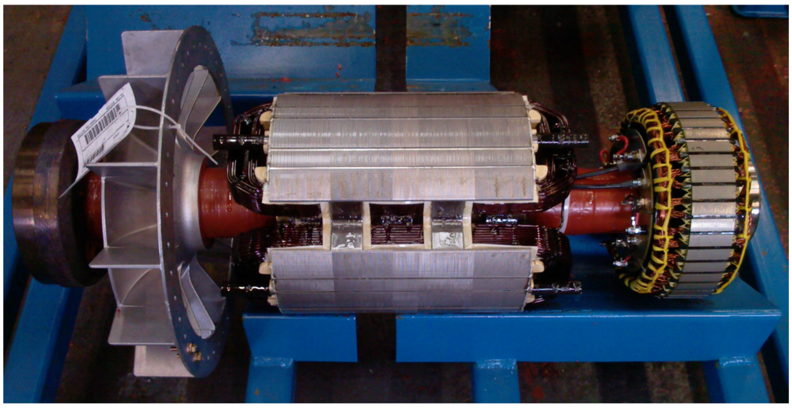

Figure 10. Rotational component assembly of a typical synchronous machine.

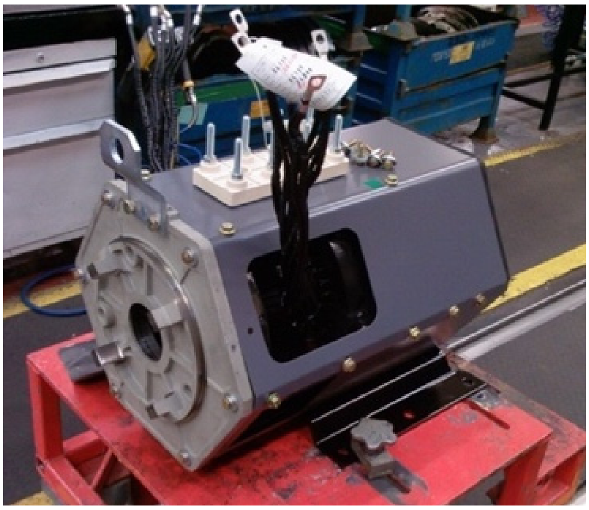

Figure 11. Complete assembly of a typical synchronous machine.

Table 3. Carbon emission comparison of a synchronous machine.

Component		Material	Mass (kg)	Carbon Emission Factor ($kgCO_2e/kg$)	Total Carbon Emission ($kgCO_2e$)
Lamination	Main stator	Electrical steel (M235-35A)	40.20	2.12 [24]	85.22
	Main rotor		27.00		57.24
	Exciter stator		6.99		14.82
	Exciter rotor		6.57		13.93
Winding	Main stator	Copper	9.6	8 [25]	76.80
	Main rotor		9.90		79.20
	Exciter stator		2.67		21.36
	Exciter rotor		0.95		7.60
Housing		Low carbon steel	23.84	2.8 [48]	66.75
End brackets		Gray cast iron	43.45	3.41 [48]	148.16
Fan		Cast aluminium	1.98	13.1 [48]	25.94
Shaft		Medium carbon steel	19.00	2.8 [48]	53.20
Total			192.14	650.22	

The total carbon emission of each component is the product of the material's mass and carbon emission factor. The emission factors considered here would be from the highest if a range of values were given per material in the previous sections.

The culmination of the various material inputs ultimately gives the total carbon emissions associated with the raw material of the end product, which is quantified at 650.22 kgCO_2e for the benchmark synchronous machine.

A breakdown of the percentage distribution of carbon emissions by component is shown in Figure 12, which reveals insightful patterns. Machine winding (in stator/rotor) appears to have the highest carbon emission value of 29% of the whole machine due to copper's relatively high carbon emission factor, even though winding ranges in the medium of total mass per component. Although aluminium has a slightly higher carbon emission factor than copper, the density of aluminium is around three times lower, which could result in a much lower overall winding mass. However, the higher resistance of aluminium should also be considered, as a larger amount of coil would be needed to replace copper. The lamination of electrical steel has the second highest share of carbon emission in the machine, at 26%.

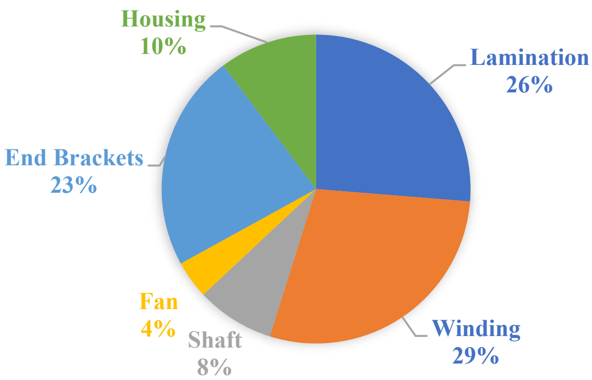

Figure 12. Carbon emission distribution of machine components.

Passive component gray cast iron end brackets have a 23% share in the overall machine emission. However, the material has a relatively low carbon emission value; a large amount of material used marks the component as the third highest for overall carbon emissions of the machine. Low- and medium-carbon steel housing and shafts have the fourth and fifth carbon emission shares of 10% and 8%, respectively. The fan component has the lowest carbon emissions of the entire machine at 4%.

5.2. Carbon Emission Reduction

The windings used in electrical machines necessitate electrical conductivity, making copper coils the preferred choice for traditional machine windings. This preference is due to the inherent strengths of copper, including its reliability, durability, and efficient heat transfer properties. However, suggestions in recent literature advocate for the substitution of aluminium coils for copper [65]. Such suggestions are primarily motivated by the lower cost and lower mass density of aluminium. It is worth noting that while aluminium offers cost advantages, certain trade-offs, such as higher electrical resistivity, result in higher winding losses.

Although aluminium coils have a slightly higher carbon emission factor per unit mass (9.16 kgCO_2e/kg) than copper coils (8 kgCO_2e/kg), the main advantage is the significantly lower density of aluminium, which can be up to three times less dense than copper. This lower density translates into a significantly reduced overall mass when using aluminium coils of the same dimensions as copper coils. As a result, the carbon emissions associated with aluminium coils can be lower than those of their copper counterparts when the entire coil assembly is considered. However, since aluminium possesses lower electrical conductivity than copper, to achieve the same power output, using aluminium would require a larger wire diameter and, therefore, a larger motor. Figure 13 shows the CAD sectional profile of the rotor and stator core of a 4-pole salient pole synchronous machine, in which the rotor windings are shown in red and stator windings are shown in blue.

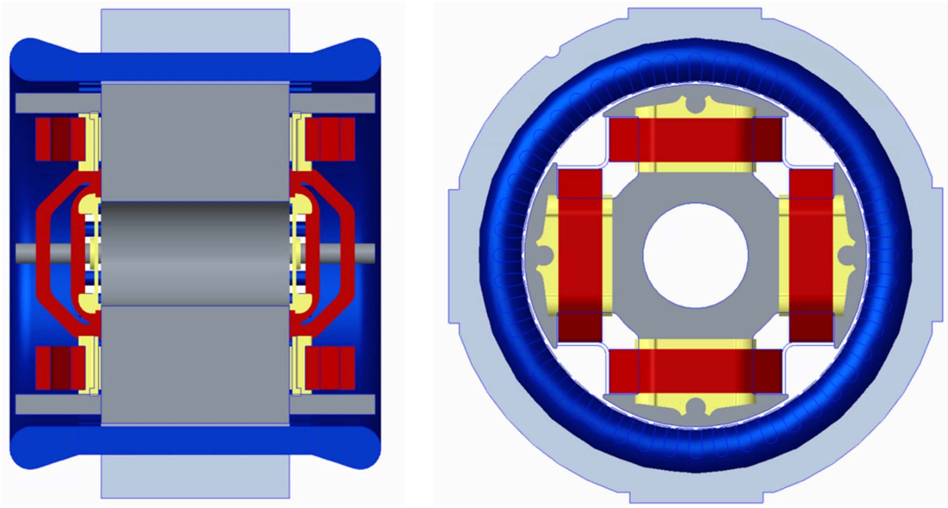

Figure 13. Axial and radial cross-sectional profiles of a salient pole synchronous machine.

As shown in the figures above, inspection of the rotor reveals that the poles are fitted with field windings. In the existing designs using copper (Cu) windings, there is unused space within the inter-pole area. This provides a promising opportunity to explore the use of aluminium (Al) windings with an increased cross-sectional area. By implementing this approach, it will be possible to maintain losses at a similar level to those observed with copper windings while utilising the available space.

Table 4 compares the losses and carbon emissions between copper and the different coil arrangements of aluminium windings. In this context, Al 1 refers to aluminium wire with higher resistance but identical dimensions to the current copper arrangement. In contrast, Al 2 refers to aluminium wire with the same resistance, but larger dimensions compared to the existing copper arrangement, which would still fit within the available space in the interpolar areas.

Table 4. Copper and aluminium characteristic comparison of the rotor winding.

	Main Rotor		
	Cu (Baseline)	**Al 1**	**Al 2**
Resistance (Ω)	0.57	0.88	0.57
Joule losses (watts)	2900	4460	2900
Diameter (mm)	2.65	2.65	3.29
Volume (mm^3)	1.01×10^6	1.01×10^6	1.56×10^6
Mass (kg)	9.0	2.73 (−70%)	4.20 (−53%)
Carbon Emission (kgCO_2e)	72	25.04 (−65%)	38.50 (−46%)

The data for Al 1 shows that a significant increase in winding losses is observed when the same amount of aluminium is used to replace copper coils while maintaining the same winding dimensions in terms of diameter and length, as aluminium coils generate a winding loss of 4460 W, as opposed to the 2900 W observed with the copper coils.

As for Al 2, this arrangement includes a wider winding area and a higher fill factor. In particular, compared to Al 1, the Al 2 arrangement involves increasing winding mass and volume. Despite these changes, it is noteworthy that the Al 2 configuration still achieves a significant 53% reduction in mass and a 46% reduction in carbon emissions compared to the copper winding arrangement.

It is, therefore, possible to use aluminium winding with a larger cross-sectional area while keeping losses constant. This adaptation makes it possible to reduce mass and carbon emissions without compromising the electromagnetic properties of the machine.

Due to its low carbon emission values, carbon steel appears to be the optimum option for all passive components, such as housing, end brackets, fan, and shaft. Yet, due to its higher density compared to cast iron and aluminium, carbon steel will have a slightly higher overall component mass. Grey cast iron also has relatively low carbon emission values and lower mass density compared to carbon steel. By replacing cast iron end brackets and cast aluminium fans with medium carbon steel, the carbon emission value of the whole machine could be reduced, but the mass will be increased. Table 5 shows the carbon emission comparison of different end brackets and fan materials. It is noteworthy that the mass of the new materials used for comparison has been determined based on their respective densities and the mass of the original material. Importantly, this calculation maintains a constant component volume throughout the comparison process.

Table 5. Carbon emission comparison of end bracket materials.

Component	Material	Density (g/cm^3)	Mass (kg)	Carbon Emission Factor ($kgCO_2e/kg$)	Total Carbon Emission ($kgCO_2e$)
End brackets	Grey cast iron [1]	7.15	43.45	3.41 [48]	148.16
	Medium carbon steel	7.85	47.70	2.80 [48]	133.57
	Cast aluminium	2.70	16.41	13.10 [48]	214.94
	Stainless steel 304	8.00	48.62	6.15 [26]	298.98
Fan	Cast aluminium [1]	2.70	1.98	13.10 [48]	25.94
	Medium carbon steel	7.85	5.76	2.80 [48]	16.12
	Grey cast iron	7.15	5.24	3.41 [48]	17.88
	Stainless steel 304	8.00	5.87	6.15 [26]	36.08

[1] The coloured rows represent the original material used for each component.

By replacing cast iron end brackets with medium carbon steel, the carbon emission value of the whole machine will be reduced by around 15 $kgCO_2e$, yet the mass will be increased by around 4 kg.

When switching from one metal material to another, replacing cast iron end brackets with medium carbon steel is the most favourable overall choice. Carbon steel has lower carbon emissions, which fits well with the overall aim of reducing the environmental impact of electrical machines.

Despite its relatively small mass, the fan of the baseline machine significantly impacts the overall carbon emissions associated with the machine. This is primarily due to the high carbon emission factor inherently associated with aluminium, the material from which the fans are typically constructed.

Grey cast iron and medium carbon steel stand out for their commendable reduction in carbon emissions, with 8.06 $kgCO_2e$ (30.58%) and 9.82 $kgCO_2e$ (37.86%), respectively. This reduction is offset by some increase in component mass, of 3.26 kg (166.65%) and 3.78 kg (190.73%), respectively, compared to the aluminium fan. In the cases above, for the brackets and fan, the carbon reductions are achieved at the penalty of some increased mass by using carbon steel or cast iron. The increase in mass is generally acceptable for the typical applications where such machines are used, being land-based and stationary.

As for the shaft, since the original material, carbon steel, used in the machine already appears to be the ideal option, reducing the mass of these components could be advantageous.

The machine shaft is pivotal as the rotating component responsible for transmitting torque, power, and motion. When subjected to torque or torsional forces, it experiences the generation of shear stresses within its structure. This shear stress distribution is not uniform but varies from zero at the centre axis to a maximum at the outer surface of the shaft. Retaining this excess material, which contributes to mass, does not significantly enhance the shaft's capacity to withstand torsional loads. It adds weight without a commensurate benefit regarding strength or performance improvement. This insight forms the basis for considering an alternative approach—the use of hollow shafts.

The baseline machine has a core length on the shorter side, with low primary rotor inertia. Thus, the hollow shafts could be acceptable without affecting other rotating components' performance. The inner diameter of the hollow shaft can be as large as necessary, providing that the stiffness and shear stress remain within the safety region. For the baseline machine, the stress is limited to 34 MPa, which has to be at least 1.5 times the shear stress on the shaft drive-end side.

Hollow shafts are conventionally manufactured with forging and deep-hole drilling, which are expensive and will generate an additional carbon footprint from the material waste and machining. New and innovative hollow shaft manufacturing techniques such as the cold forging process [66,67] and flexible skew rolling [68] offer eco-friendly options with cost cutting, energy and waste reduction.

Table 6 provides a concise summary of hollow shafts with different internal diameters, allowing for a comparative analysis with the solid shaft for several key parameters such as stiffness, total deformation, shear stress, and mass and carbon emissions.

Table 6. Comparison between solid and hollow shafts.

Shaft Option	Stiffness (Nm/rad)	Mass (kg)	Shear Stress (MPa)	Total Carbon Emission ($kgCO_2e$)
Solid	3.31×10^5	18.90	8.49	47.25
Hollow (15 mm)	3.30×10^5 (−0.4%)	18.00 (−4.8%)	8.53 (+0.6%)	45.00 (−4.8%)
Hollow (20 mm)	3.27×10^5 (−1.3%)	17.26 (−8.7%)	8.64 (+1.8%)	43.15 (−8.7%)
Hollow (25 mm)	3.21×10^5 (−3.1%)	16.31 (−13.7%)	8.86 (+4.5%)	40.78 (−13.7%)
Hollow (30 mm)	3.10×10^5 (−6.4%)	15.14 (−19.9%)	9.31 (+9.7%)	37.85 (−19.9%)
Hollow (35 mm)	2.92×10^5 (−12%)	13.75 (−27.3%)	10.15 (+19.6%)	34.38 (−27.3%)
Hollow (40 mm)	2.62×10^5 (−20.9%)	12.17 (−35.6%)	15.90 (+87.4%)	30.43 (−35.6%)

Looking at the stiffness of the shaft, it can be seen that the percentage reduction approximately doubles for every 5 mm increase in the internal diameter. This trend follows a reduction of 20.9% observed for the shaft with an internal diameter of 40 mm.

There are notable variations when assessing the shear stress for the drive-end (D.E.) of the shaft, which has a nominal diameter of 55 mm. The solid shaft configuration records a shear stress value of 8.49 MPa, while the counterpart with the largest internal diameter of 40 mm records a significantly higher shear stress value of 15.9 MPa.

It is important to compare these values with the established stress limit of 34.47 MPa. This limit represents the threshold beyond which structural integrity and safety may be compromised. Remarkably, even with the largest hollow shaft configuration considered, the shaft remains well within the safety margin. Specifically, this shaft design can transmit a substantial 2.2 times the full load torque, highlighting its robustness and ability to handle significant mechanical loads while maintaining the required safety margins.

6. Conclusions and Outlook

All sectors of the economy are committed to reducing carbon emissions in response to environmental pressures, encouraging the widespread use of electric machines in transport and industry. This paper aimed to fill the existing gap in the literature by focusing on the carbon emissions from the manufacturing phase from readily available life cycle inventory (LCI) datasets, supplemented by relevant findings from the scientific literature.

Overall, the mining process of raw materials can be significantly impactful during the primary production stage, including the electricity used, the blasting process and the fuel burned in industrial machinery. This paper focused mainly on virgin materials, with recycled materials expected to have lower emissions. Future research could compare emissions from virgin and recycled materials and explore technologies to reduce emissions from primary production. Additionally, new materials could be investigated to replace the current mainstream component materials, reducing carbon emissions and weight while maintaining or enhancing the overall machine performance.

A case study of a synchronous machine is also presented to investigate the impact of changing materials from a carbon emission perspective. The analysis showed that copper winding is the main contributor to carbon emissions for such machine types due to its high mass density and carbon emission factor. Further investigation revealed potential approaches to reduce carbon emissions in the base machine. For example, a strategic substitution of copper for aluminium winding for the rotor while maintaining an equivalent resistance level for wound field synchronous machines can result in significant savings—up to 53% and 46% in mass and carbon emissions, respectively, compared to the original component. In addition, carbon steel is a viable option for reducing carbon emissions, but at the cost of increased component mass and, hence, overall machine weight, which may be acceptable for land-based stationary applications. Recognising that carbon emissions are a function of material mass, the paper explored the potential for optimising critical components. For example, using a hollow shaft within shear stress safety margins reduces the carbon emissions of such a design by up to 35.6% compared to a solid shaft.

Future research will extend the scope to include these additional life cycle stages. Applying a cradle-to-cradle/grave LCA approach makes it possible to achieve a more comprehensive assessment of the environmental impact of electrical machines over their entire life cycle, including the primary production, operation, end-of-life, and recycling phases.

The need for specific carbon emission data for certain materials in the literature highlights the importance of ongoing research and data collection in materials science and LCA. As advances are made and more information becomes available, more accurate and detailed assessments of the environmental footprint of materials will be possible. The data reviewed in this paper will advance our understanding of materials in several ways and serve as a basis for selecting appropriate materials. Future research will focus on using the data in this paper to compare different types of electrical machines and to include operational and recycling considerations in the studies.

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