Carbon Emission Analysis of Electrical Machines

Xuebei Zhang
Department of Electrical and Electronic Engineering
University of Nottingham
Nottingham, UK
xb.zhang97@gmail.com

Zeyuan Xu
Department of Electrical and Electronic Engineering
University of Nottingham
Nottingham, UK
epzzx@nottingham.ac.uk

Chris Gerada
Department of Electrical and Electronic Engineering
University of Nottingham
Nottingham, UK
eezcg@nottingham.ac.uk

David Gerada
Department of Electrical and Electronic Engineering
University of Nottingham
Nottingham, UK
ezzdg2@nottingham.ac.uk

***Abstract* — The industry places increased importance on carbon reduction. Many are focused on lowering the fuel consumption of electrical machines, however, carbon emissions from the acquisition of raw materials and the energy consumption of manufacturing processes also contribute significantly. Therefore, a carbon emission analysis model is particularly necessary for electrical machines. This paper presents an evaluation method for the carbon emissions of the production of industrial synchronous generator. The results concluded can be used to reduce the carbon emission of electrical machines, material waste and energy consumption, moreover, identify a detailed investigation of the impact between raw material acquisition, manufacturing process planning and carbon emissions.**

I. INTRODUCTION

All industries currently face the challenge of major carbon reduction due to global warming, with the carbon tax introduced, companies are trying to optimise the key requirements of electrical machines to reduce fuel consumption which contributes massively to emissions of carbon footprints[1].

In addition to improving machine efficiency, the energy used in raw material acquisition and components manufacturing processes also accounts for a significant amount of carbon emissions. Therefore, all performance specifications and requirements are vital for machine applications. Consequently, improving motor performance with an insight into their associated embodied carbon is of great significance to both environmental protection and energy sustainability.

Studies on the carbon emission of electrical machines have not yet been well established and there are limited initiatives and calculation methods that provide only guidelines for assessing the carbon footprint. It is rather difficult to apply standards such as the greenhouse gas protocol (GHG) and ISO 14064 on an organisation level with their lack of clear format and procedure [2].

Based on the scientific literature and methods from other industries and standards, this paper aims to demonstrate a method to calculate the carbon emissions of major components materials and the energy consumption during the manufacturing process of electrical machines and provides a carbon footprint of an industrial 4-pole self-excited synchronous generator with a power rating of several hundred kVA range.

II. CARBON EMISSION ANALYSIS

A. Main Methodologies

Academic literature provides three core methods for analysing carbon footprint: input-output analysis (IOA), life-cycle analysis (LCA) and hybrid (IO-LCA) are shown in Fig. 1 [3]. The selected method for analysis is dependent on the scale of the product being studied.

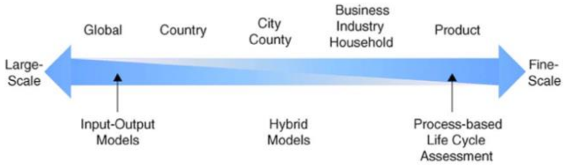


Figure 1: Schematic of carbon footprint applications

1) Input-Output Analysis (IOA)

The amount of carbon footprint associated with a product can be analysed with the input-output method, given that they are caused directly and indirectly through a procedure or are compiled over the life stages. The product that has been analysed can be at the national level or for a sector-specific assessment[4].

2) Life-Cycle Analysis (LCA)

Life-Cycle Analysis (LCA) is an ISO accredited carbon emission analysis method that is commonly used across the industries in analysing the impact on the environment, especially 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 its life stages[5].

The principle of LCA calculation is that the total environmental impact of a material is the multiple of the quantities of the material and their associated emission factor. Based on the scale of electrical machines, the LCA method shown in Fig. 2 would be the best for calculating the carbon emissions of raw material acquisition. However, this approach is limited to analysing carbon emissions for manufacturing processes due to its lack of precise statistics relating to energy consumption throughout the product life stage[6].

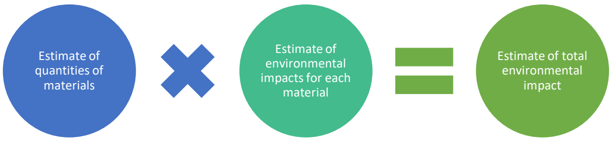


Figure 2: Principle of LCA calculation

a) Life-Cycle Inventory (LCI)

The main material inventory used for LCA was acquired from Inventory of Carbon & Energy (ICE)[7], Cambridge Engineering Selector (CES) software[8], and other scientific research journals[9, 10]. The data collected from these databases are all within a close range, therefore an average value was used for each material, and these data are referred to as carbon emission factors in the unit of kgCO2e/kg.

3) Hybrid Analysis (IO-LCA)

The hybrid analysis has been adapted in the evaluation of the carbon emission of an industrial synchronous generator in this paper. 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 [11].

B. Carbon emission of raw material production and machining

Fig. 3 and 4 [8] [12] shown below are the carbon emission per kilogram of ferrous and non-ferrous metal extracted. It has been suggested by Gutowski that the energy required for material processing is insignificant compared to the total energy consumed for machine operation [13]. Moreover, the carbon emission generated from the primary process of material manufacture is generally higher than that of the secondary forming process.

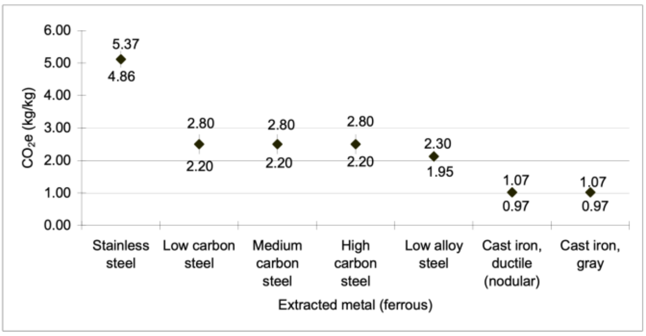


Figure 3: Carbon emission of extracted ferrous metal

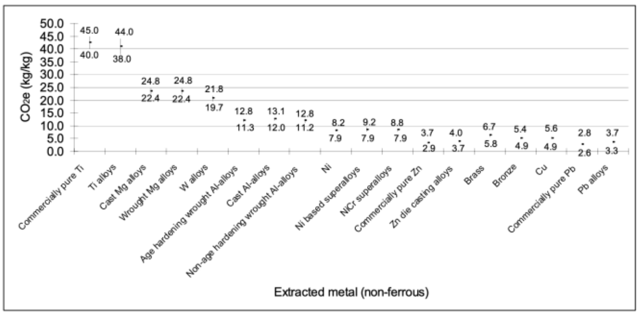


Figure 4: Carbon emission of extracted non-ferrous metal

By comparing the energy requirements of different metal alloys, it has been found that the energy consumption is much lower when a product has been machined at a higher volumetric removal rate or machined at a higher speed. Furthermore, the variety of material being machined can also affect the energy consumption, such that a higher strength, tougher material requires higher specific energy for machining [12].

Thus, reducing the energy consumed during machining leads to reducing the carbon emissions associated with industrial activities.

C. Carbon emission model for manufacturing processes

Since carbon emissions can be directly related to energy production, previous studies by Jeswiet and Kara [14] have demonstrated a technique that directly links the energy consumed during manufacturing processes to the carbon emissions generated relating to electrical energy. During a product's manufacturing stage, the required materials and energy would go through necessary operations and procedures, which are converted into the final product and its associated carbon emission[15]. A carbon emission analysis framework has been proposed by Wang et al. as shown in Fig. 5 [16].

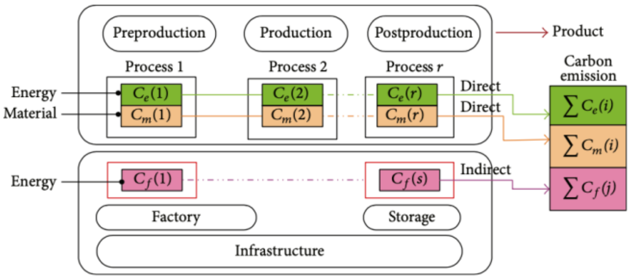


Figure 5: Carbon emission analysis framework for a product manufacturing

Based on the diverse forms of input resources and energy types, carbon emissions are divided into direct and indirect emissions. Direct emissions mostly refer to the emissions caused during the manufacturing phase, which includes the consumption of machine operational energy and raw materials. Indirect carbon emissions occur during other non-operational stages during manufacturing, which refers to the carbon emissions caused by the energy consumed by electrical devices.

III. METHODOLOGY

The methodologies presented here are for the analysis on the benchmark machine components material and manufacturing process. The main components under investigation are the wound rotor, wound stator, exciter, fan, and cast housing parts. The manufacturing processes presented in this paper are particular for this benchmark machine, which includes the stamping and welding process of lamination cores and needle winding for the rotor, stator, and exciter.

A. Raw material acquisition

The calculation of carbon emission of raw material can be expressed as [1]:

$$R_{CE} = M_{sheet} \times CF_{sheet} \tag{1}$$

Where:

R_{CE} Carbon emission of raw material acquisition (kgCO^{2}e)
M_{sheet} The weight of material consumed (kg)
CF_{sheet} The carbon emission factor of the material (kgCO^{2}e/kg)

B. Carbon emission from energy consumption during manufacturing

The carbon emission of energy consumed during a general manufacturing process can be calculates as [2]:

$$M_{CE} = E_{machinery} \times CF_{energy} \tag{2}$$

Where:

M_{CE} The carbon emissions from electricity used by the machines (kgCO^{2}e)
$E_{machinery}$ The energy consumed during manufacturing (GJ)
CF_{energy} The carbon emission factor of energy (Which is 0.213 kgCO^{2}e/kWh from the latest 2021 UK government database[17])

1) Lamination Stamping Process

Gao et al. [18] presented a method for evaluating the carbon emissions in the stamping process, the procedures involved in their study are described as follows:

- Raw material acquisitions
- Blanking
- Handling
- Forming
- Cutting
- Auxiliary utilisation

Through the analysis of the definition of stamping procedures, CE$_{total}$, the total carbon emission from stamping can be expressed as the sum of carbon emissions produced by several procedures related to the stamping process, mainly from material and energy consumption.

$$CE_{total} = R_{ce} + \sum_{i=1}^{N} M_{CE} + \sum_{j=1}^{K} H_{CE} + C_{CE} + A_{CE} \tag{3}$$

Where:

R_{ce} The carbon emission from the raw materials
M_{CE} The carbon emission from the production of electricity used for punching and forming
N Number of the machines
H_{CE} The carbon emissions from the production of electricity by transferring components
K Number of robots used for transferring the component
C_{CE} The carbon emissions from the generation of electricity by cutting
A_{CE} The carbon emissions from the production of tools and lubricants

Based on the stamping procedure used in this paper, only R_{ce}, the carbon emissions of raw materials and M_{CE}, the carbon emissions caused using electricity during punching stage are considered. Therefore, the equation used can be simplified to:

$$CE_{total} = R_{ce} + \sum_{i=1}^{N} M_{CE} \tag{4}$$

$$E_{stamping} = F(t)v(t)dt \tag{5}$$

Where:

$E_{stamping}$ The energy consumed by stamping machine to be substituted into equation (2)
$F(t)$ The stamping force (refer to Table 1)
$v(t)$ The stamping velocity (refer to Table 1)

Table 1: Parameters of stamping machine [19]

Pressing force in kN	Number of strokes up to 1/min	Stroke in mm
630kN	450	10 to 80

2) Lamination Welding Process

The welding analysis was based on the conceptual framework proposed by Zhang et al. [20] which uses CO^2 arc welding during their manufacturing stage.

The method used for lamination welding in the benchmark machine could be either tungsten inert gas (TIG) welding, or metal inert gas (MIG) welding. In this paper, only the MIG welding process is considered for carbon emission analysis. MIG welding requires the use of a welding feed wire, which continually moves through the welding gun to generate the spark that melts and form the weld. The process requires the use of argon or argon-CO^2 as the protection gas depending on the welding material.

During a welding process, the consumption of electrical energy, welding wire, and protective gas can vary slightly based on the operational condition and the welding operator.

The usage of welding wire can be calculated with the equation below, which is linked with the welding area, the length of welds, and the splash rate of welding wire. As well as the quality of the welding wire and the welding skill of the operator [20].

$$m_{welding} = \frac{\sum_{i=1}^{n} A \times Li' \times \rho_{welding}}{1 - \lambda} \tag{6}$$

Where:

$m_{welding}$ The amount of welding wire consumed
n The number of cross-section of welds
A The cross-sectional area
Li' Total length of cross-section of welds
$\rho_{welding}$ Density of the welding wire
λ Splash rate of welding wire (2% according to the statistics in the research study)

$$T_{welding} = v \times m_{welding} \tag{7}$$

Where:
$T_{welding}$ The time required for welding the parts
v The feed-rate of the welding wire

The energy consumption of the welded component can be calculated by

$$E_{welding} = T_{welding} \times U \times I \tag{8}$$

Where:
$E_{welding}$ The energy consumed
U The welding voltage (refer to Table 2)
I The welding current (refer to Table 2)

The carbon emission during welding from shielding gas can be calculated by:

$$m'_{gas} = T_{welding} \times Q_{gas} \times \rho_{gas} \tag{9}$$

Where:
m'_{gas} The carbon emission from shielding gas used
Q_{gas} The flow of shielding gas (refer to Table 3)
ρ_{gas} The density of shielding gas

The total carbon emission during welding can then be calculated as:

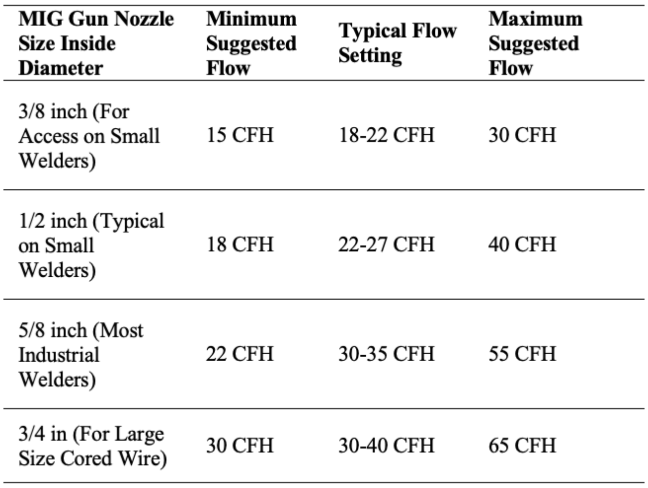
$$CE_{welding} = m_{welding} \times k_{welding} + m'_{gas} \times k_{gas} + E_{welding} \times k_E \tag{10}$$

Where:
$CE_{welding}$ The carbon emissions from welding
$k_{welding}$ The carbon emission factor of welding wire
k_{gas} The carbon emission factor of the shielding gas (refer to Table 4)

Table 2: Parameters used in MIG welding[21]

Technique	Thickness of Work	Wire diameter	Amps	Volts	Wire Feed
Dip. Vertical	3mm (Butt weld)	1mm	160	18	7 m/min

Table 3:MIG shielding gas flow rate[22]



MIG Gun Nozzle Size Inside Diameter	Minimum Suggested Flow	Typical Flow Setting	Maximum Suggested Flow
3/8 inch (For Access on Small Welders)	15 CFH	18-22 CFH	30 CFH
1/2 inch (Typical on Small Welders)	18 CFH	22-27 CFH	40 CFH
5/8 inch (Most Industrial Welders)	22 CFH	30-35 CFH	55 CFH
3/4 in (For Large Size Cored Wire)	30 CFH	30-40 CFH	65 CFH

Table 4: Emissions from Argon gas[23]

	Energy kWh/m^3	CO$_2$/m^3	CO
Production	0.64	0.385	

3) *Winding Process*

The energy consumed during winding process can be calculated with the equation:

$$E_{winding} = P \times t \tag{11}$$

Where:
$E_{winding}$ The energy consumed during welding
P The power of winding machine (refer to Table 5)
t The time required for the winding process

The time required for the winding process can be determined from the machine speed and length of coil.

$$t = \frac{L}{v} \tag{12}$$

Where:
t The time taken for winding
L The length of copper coil used in winding
v The machine winding speed

Table 5: Parameter of needle winding machine [24]

Axis speed mm/sec	Speed of winding spindle 1/min	Power
Up to 500	Up to 1000	4kVA

4) *Other Processes*

Carbon emission through energy consumption of other manufacturing processes of the machine such as impregnation procedure, shaft preparation, wire termination, and unit assembly are determined using the methodology published by the Chalmers University of Technology [25]. The energy consumption for iron and aluminium casting for the fan and housing components are acquired from the study by Salonitis et al [26].

The overall carbon emission value obtained with the carbon emission factors and specific energy consumption from the LCI should be viewed as close approximations, as different specifications of machines and carbon emission factors obtained from different institutions and regions would appear differently.

IV. RESULTS AND DISCUSSION

The results concluded in this paper are prepared with the guidance of the carbon emission analysis framework on the main components of an industrial 4-pole synchronous generator with a power rating of several hundred kVA ranges.

As shown in Table 6 below, the total carbon emission of end-product raw material is 561.58 kgCO^{2}e for the benchmark industrial synchronous generator, the value presented excluding any waste material.

Table 6: Carbon Emission of raw material acquisition from benchmark machine

Component	Material	Weight (kg)	Carbon Emission Factor ($kgCO_2e/kg$)	Total Carbon Emission ($kgCO_2e$)
Lamination	Electrical Steel	80.76	3.12	251.97
Coil	Copper	23.23	6.7	155.64
Shaft	Mild Steel	19.00	2.2	47.50
Fan	Cast Aluminium	1.98	13.1	25.94
Housing	Cast Iron	43.45	1.07	46.49
	Mild Steel	23.84	2.5	59.59
Total				**587.13**

As shown in Fig.6 below, electrical steel laminations have the highest carbon emission ratio of 45%, followed by the copper winding of 23%. Although the embodied carbon per kilogram for electrical steel is not the highest compared to copper or cast aluminium alloys, a great amount of material was consumed during the lamination production stage. In this paper, the wasted electrical sheets from stator lamination stamping are assumed to be re-used for rotor lamination stamping. However, if new electrical sheets were assumed to be used for rotor lamination stamping, then the amount of electrical steel consumed and wasted would be estimated to be doubled, which would lead to twice the carbon emission for the stamping process.

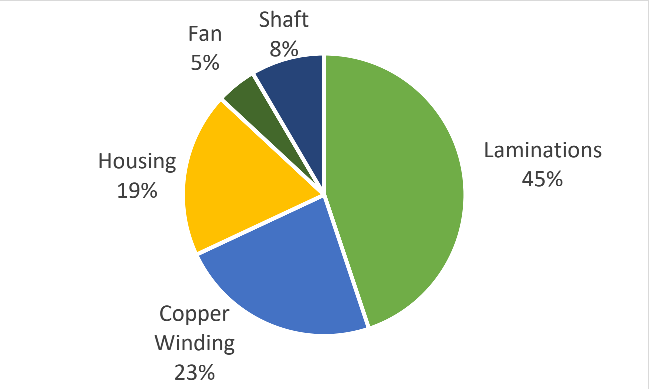


Figure 6: Carbon emission distribution of raw material

The benefits of cast aluminium alloys are the low melting temperature and lightweight, but it has the highest embodied carbon per kilogram of material consumed. By comparing to electrical steel, the fan is 2.5% of the mass of lamination, but 10% of the total carbon emission of laminations.

Table 7 below presents the total carbon emission of energy consumed through manufacturing processes based on the calculations and methods mentioned in section III.

The casting of iron and aluminium has the highest specific energy consumption per kilogram of the material casted, and aluminium casting consumes three times more energy than gray iron casting.

The embodied carbon for welding presented in Table 7 only shows the carbon emission from electricity consumed, which does not include the carbon emission from protection gas and welding wire consumed. If to include these data, the total embodied carbon for welding would be 68.06 kgCO2e.

Table 7: Carbon emission through energy consumption for manufacturing processes

Component	Secondary Manufacturing Method	Energy Consumption (kWh)	Total Carbon Emission ($kgCO_2e$)
Lamination	Stamping	6.94	1.48
	Stacking	2.04	0.43
	Welding	24.04	5.12
	Impregnation	2.21	0.47
Coil	Enamelling	11.62	2.48
	Winding	1.132	0.24
	Wire termination	0.68	0.14
Shaft	Turing	2.05	0.44
	Spline milling	1.4	0.3
	Surface hardening	0.28	0.06
Fan	Aluminium Casting	20.22	4.31
	Machining	6.14	1.31
	Cleaning	0.87	0.19
Housing	Iron Casting	158.16	33.69
	Cutting	0.05	0.01
Assembly	Press fit	0.59	0.13
	Balancing	0.016	0.004
Total		**238.438**	**50.80**

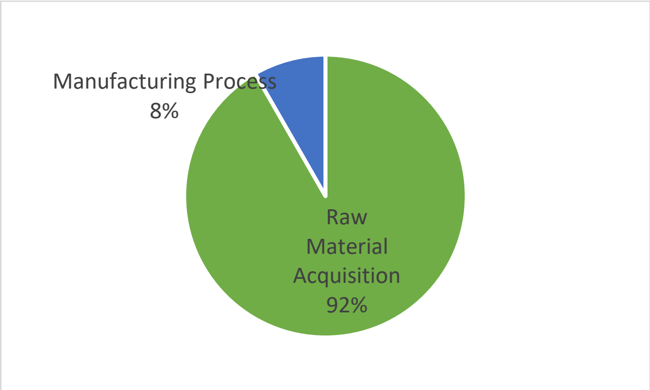


Figure 7: Carbon emission distribution between raw material and manufacturing process of benchmark machine

As shown in Fig.7 above, the largest contributor for the carbon emissions in the benchmark industrial synchronous generator is the raw material acquisition which is dominated by 92% of the overall carbon emission value. Which the production of raw material includes material harvesting and transportation to manufacturing sites, which is attributable to the carbon footprint.

V. CONCLUSION

This study sets out to analyse the carbon emission of electrical machines based on scientific literature and integrate approaches previously developed and appears to be the first study to evaluate carbon emissions during the manufacturing process of electrical machines.

Raw material acquisition dominated the majority of 92% of carbon emission of benchmark industrial synchronous generator compared to only 8% of the manufacturing process. With 45% of electrical steel lamination of the highest carbon emission among the component materials excluding waste from stamping.

Reducing the material waste from stamping would significantly decrease the overall carbon emission of electrical machines if the stamped lamination waste has not already been used for the rotor laminations. Thus, one strategy of reducing waste is to re-use the recycled waste from stator laminations, given that it is in an appropriate diameter range.

Casted aluminium alloy has the highest specific carbon emission factor and specific energy consumption. Although aluminium alloy is lightweight, which will benefit the overall machine performance, the high carbon emission during manufacturing may be balanced with this advantage. The embodied carbon from casted gray iron is three times less than aluminium alloys, it is also almost three times denser than aluminium alloys which is something that needs to be considered when choosing materials for the components. The cost should also be a factor to consider when choosing materials with lightweight and low embodied carbon.

The insight gained from this study may be of assistance during the designing and manufacturing phases to reduce material waste and improve manufacturing efficiency. Consequently, improving machine performance with an insight into their associated embodied carbon is of great significance to both environmental protection and energy sustainability.

VI. ACKNOWLEDGEMENT

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