Applying The Carbon Scope Framework for Decarbonisation in a South African High Alloy Foundry

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ABSTRACT

Carbon emissions constitute a growing concern for South Africa's manufacturing sector, particularly the foundry industry. Despite national commitments to achieve net-zero emissions by 2050 and the implementation of carbon tax regulations, many foundries have been slow to adopt effective decarbonisation measures. This study quantifies the carbon footprint of a high-alloy castings foundry using Scope 1, 2, and 3 methodologies, converting data from molten metal production, electricity use, logistics fuel, and staff transport into CO_2-equivalent emissions. Results showed that electricity was the dominant contributor at 83.7% (27.6–161.9 tCO_2), followed by gas at 13.4% (10.25–25.86 tCO_2), diesel at 2.3% (0.51–4.48 tCO_2), and petrol at 0.6% (<1.11 tCO_2). The study recommends adopting low-carbon fuels, automating temperature controls, implementing energy-management systems, integrating renewable energy for Scope 1 and 2 reductions, and transitioning to electric vehicles with improved logistics for Scope 3. These data-driven strategies support both national and global climate goals while promoting more sustainable foundry operations.

OPSOMMING

Koolstofvrystellings is 'n groeiende bron van kommer vir Suid-Afrika se vervaardigingsektor, veral die gieterybedryf. Ten spyte van nasionale verbintenisse om netto-nul-vrystellings teen 2050 te bereik en die implementering van koolstofbelastingregulasies, was baie gieterye stadig om effektiewe dekarboniseringsmaatreëls in te stel. Hierdie studie kwantifiseer die koolstofvoetspoor van 'n hoë-legering gietery met behulp van Scope 1-, 2- en 3-metodologieë, deur data van gesmelte metaalproduksie, elektrisiteitsverbruik, logistieke brandstof en personeelvervoer om te skakel na CO_2-ekwivalente vrystellings. Resultate het getoon dat elektrisiteit die dominante bydraer was teen 83,7% (27,6–161,9 tCO_2), gevolg deur gas teen 13,4% (10,25–25,86 tCO_2), diesel teen 2,3% (0,51–4,48 tCO_2) en petrol teen 0,6% (<1,11 tCO_2). Die studie beveel aan dat lae-koolstofbrandstowwe aangeneem word, temperatuurbeheer geoutomatiseer word, energiebestuurstelsels geïmplementeer word, hernubare energie vir Scope 1- en 2-verminderings geïntegreer word, en oorgeskakel word na elektriese voertuie met verbeterde logistiek vir Scope 3. Hierdie datagedrewe strategieë ondersteun beide nasionale en globale klimaatdoelwitte terwyl dit meer volhoubare gieterybedrywighede bevorder.

1. INTRODUCTION

South Africa is a member of the Conference of Parties (COP), a group of countries that have signed and ratified the United Nations Framework Convention on Climate Change (UNFCCC). COP members set non-binding but highly influential norms that help countries to operationalise the treaty obligations. COP decisions set climate action priorities such as phasing out coal, increasing climate financing, and establishing carbon markets under Article 6 of the Paris Agreement. As a member of the COP, South Africa has pledged its commitment to ensure net zero emissions by the year 2050.

1.1. Energy consumption in the foundry industry

The foundry industry requires a large amount of electricity to cast metallic components, which includes processes such as sand moulding, melting of metal, machining, and heat treatment. Consequently, the industry is ranked among the largest emitters of CO_2 in South Africa. Table 1 provides details of the industries with heavy energy consumption [1].

Table 1: Industries with heavy energy consumption (green, yellow, orange, and red represent a gradient from low to high consumption, with green indicating the lowest consumption and red indicating the highest) [1] [2]

Industry sector	Electricity (non-heat related)	Process heat from fuels and electricity [%]	Shares of required heat levels (Naegler *et al.*, 2015)			
			<100 °C	100 - 500 °C	500 - 1000 °C	> 1000 °C
Iron and steel	14%	86%	5%	2%	19%	75%
Chemicals and petrochemicals	25%	75%	18%	22%	48%	12%
Non-ferrous metals	52%	48%	10%	4%	20%	66%
Aluminium	60%	40%	8%	2%	18%	72%
Non-metallic minerals	17%	83%	5%	2%	30%	63%
Cement	19%	81%	5%	2%	30%	63%
Transport equipment	47%	53%	72%	10%	5%	13%
Machinery	34%	66%	57%	15%	9%	20%
Mining and quarrying	41%	59%	13%	2%	28%	57%
Food and tobacco	30%	70%	54%	46%	0%	0%
Paper, pulp, and print	32%	68%	20%	80%	0%	0%
Wood and wood products	29%	71%	37%	63%	0%	0%
Construction	35%	65%	48%	18%	11%	23%
Textiles and leather	42%	58%	100	0%	0%	0%
Unspecified (industry)	40%	60%	43%	19%	12%	25%

1.2. South Africa's Carbon Tax Act

To tackle carbon dioxide emissions from the manufacturing sector, the South African government has proposed measures that include the Carbon Tax Act. This initiative, introduced in 2019, aims to encourage factories to reduce their greenhouse gas emissions by imposing financial penalties for excessive releases. The Act outlines that companies would be required to pay a tax based on the total amount of greenhouse gases they emit over a specified period, including emissions from fuel combustion, industrial activities, and gas leaks. The proposed tax rate is R120 per ton of CO_2 released, with the collected funds intended for the National Revenue Fund [3].

1.3. Scope emission in local foundry

Kabasele *et al.* identified the key metal-casting processes that contribute to CO_2 emissions and proposed reduction strategies [4]. As outlined in Table 2, these processes fall into three scopes: Scope 1 covers direct emissions from melting, casting, and heat treatment in the foundry; Scope 2 covers indirect emissions from electricity use, notably from coal-fired power plants; and Scope 3 involves emissions from external processes, including raw material extraction and transportation of finished castings [4].

Table 2: Classification of foundry processes according to CO_2 scope emissions [4]

Stage	Process	Greenhouse gas emissions scope	Scope description
Upstream	Mining and mineral processing of pig iron	Scope 3	Emissions from purchased raw materials (not owned by the foundry)
	Processing of ferro-alloys	Scope 3	Emissions from third-party alloy producers
	Sand mining and processing	Scope 3	Emissions from extraction and processing of sand used in moulding
	Transport of raw materials to foundry	Scope 3	Emissions from vehicles not owned by the company
Internal	Moulding (sand mixing and mould preparation)	Scope 2 (electric), Scope 1 (if fuel used)	Scope 2 if using electricity; Scope 1 if using direct fuel combustion
	Melting of metal (in furnaces)	Scope 1 (fuel), Scope 2 (electric)	Scope 1 if coke or gas; Scope 2 if electric induction furnaces
	Casting (pouring molten metal into moulds)	Scope 1	Direct fuel combustion or thermal losses
	Knockout and fettling (removal of sand/runners)	Scope 1	Mechanical/thermal operations using in-house energy
	Machining	Scope 2	Electricity use for machining tools
	Heat treatment	Scope 1 (gas), Scope 2 (electric)	Depending on the energy source used
	Sand reclamation (thermal/mechanical)	Scope 2	Electricity-based equipment
Downstream	Transport of finished castings (road/flight)	Scope 3	Customer delivery by third-party logistics
	Packaging and storage	Scope 3	Emissions from purchased packaging and warehousing
	Product use and end-of-life (if applicable)	Scope 3	Emissions during product lifespan and disposal

Figure 1 illustrates the mapping of CO_2 scope emissions throughout the production of a cast iron component. In a typical cast iron foundry, the melting stage is the largest contributor, generating over 28 tCO_2-eq per ton of molten metal [5]. Another major source is the transformation of iron ore, which contributes 4.76 tCO_2-eq [6]. These stages are highly energy-intensive and are driven primarily by the combustion of carbon-rich fuels such as coal and coke. While other processes, such as sand recycling, metal pouring into moulds containing organic resins or coal dust, and the transportation of cast components, emit less CO_2, they still contribute to the overall emissions footprint. Machining and sand moulding are also energy-demanding operations, each responsible for Scope 2 emissions of 0.45 and 0.43 tCO_2-eq respectively, owing to their reliance on electricity [6] [4].

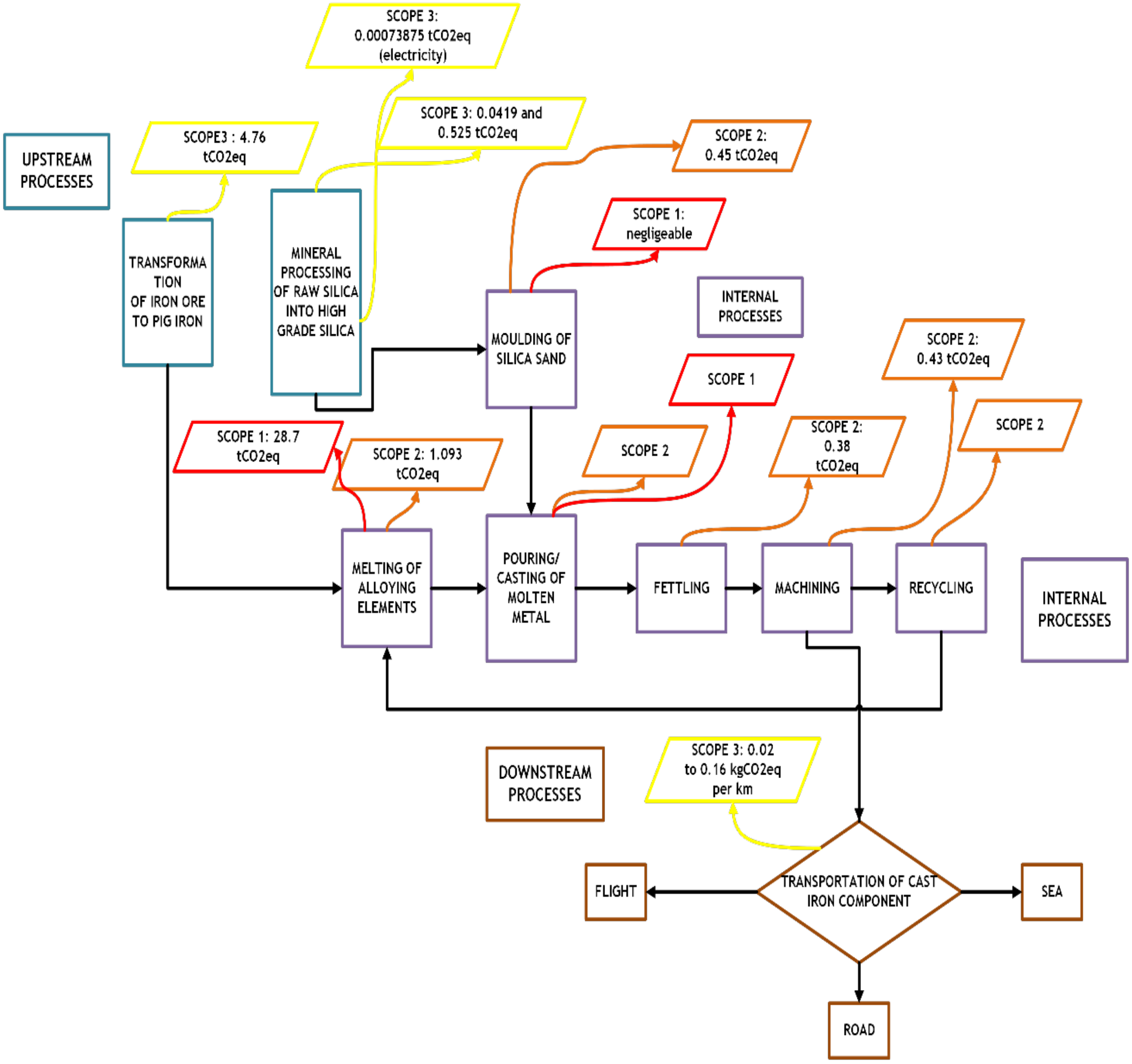


Figure 1: Carbon emissions mapped along the process flow of a typical cast iron foundry. The process closely resembles that of high-alloy casting and is presented here to guide the current study by linking each stage to relevant data structures, emission flows, and scope classifications [4].

1.4. Significance of research

Several studies have addressed the problem of accurately accounting for carbon emissions in industrial sectors. Fenner *et al.* investigated a range of carbon footprint calculation approaches and evaluated existing frameworks and methodologies. Their findings emphasise the absence of a universally established method for consistently and comparably accounting for CO_2 emissions in buildings. They advocate using a process-based breakdown of emissions, highlighting the importance of identifying carbon outputs at each stage or source in the life cycle [7].

In a similar vein, Cox *et al.* developed a three-stage framework for optimising carbon accounting in ferrous foundries, aimed at supporting net-zero objectives. Their approach, applied to two foundries in the United Kingdom, involved: (1) mapping the complete factory process through detailed flow charts of inputs and outputs; (2) calculating emissions using theoretical conversion factors and material databases to predict operational and embodied energy use; and (3) presenting the results via graphical outputs with an accessible front-end interface to encourage adoption in sand casting settings [8].

Additional contributions to the field include the work of Salonitis *et al.*, who applied life cycle assessment (LCA) to cast iron engine block manufacturing, enabling a detailed mapping of CO_2 emissions in the casting stages. Collectively, these studies establish a foundation for methodological advancements in applying carbon emission classification, particularly in South African foundries [6].

The present work takes those studies further, adopting a novel methodology that classifies CO_2 emissions according to Scopes 1, 2, and 3 in a way that is both systematic and intuitive. Scope 1 encompasses direct emissions under the immediate control of the foundry, such as fuel use and on-site combustion, and can be addressed through operational changes and optimised processes. Scope 2 relates to indirect emissions from purchased energy, particularly from energy-intensive processes, and can be reduced through improved energy management, higher-quality raw materials, and minimised production defects. Scope 3 covers other indirect emissions, such as those from supply chains and transportation, which, while more difficult to influence, can be mitigated through strategic procurement, better logistics, and collaboration with stakeholders. By framing emissions in this intuitive way, foundries could readily identify priority areas for intervention and implement targeted strategies to reduce carbon emissions.

This research has great significance in advancing sustainable practices in the cast iron foundry industry. By systematically mapping and analysing CO_2 emissions in critical processes, it equips industries with actionable insights to enhance energy efficiency and to minimise the environmental impact. The study directly addresses the pressing issue of carbon emissions in energy-intensive sectors, which are among the largest contributors to climate change globally. It also serves as a cornerstone for aligning foundry operations with international environmental standards and sustainable development goals, thereby driving meaningful progress in combating global warming. The importance of this research lies in its dual role: supporting local industries in adopting cleaner technologies and contributing to the global initiative to mitigate climate change. Its outcomes have the potential to inspire transformative practices in foundries while reinforcing their commitment to sustainability and environmental responsibility.

1.5. Problem statement

Despite the growing number of carbon emissions accounting methods, local foundries lack a practical and context-specific framework for mapping and addressing emissions according to carbon scopes. Without such a methodology, foundry managers face difficulties in identifying priority emission sources and aligning reduction strategies with both operational realities and broader national imperatives. This gap is particularly pressing in South Africa, where the implementation of a carbon tax and commitments to international climate agreements demand measurable and effective carbon reduction. An approach that enables intuitive identification of Scope 1, 2, and 3 emissions could empower foundries to adopt strategies that not only meet compliance requirements but also enhance their competitiveness, sustainability, and industry reputation.

1.6. Aim

This study aims to map and analyse carbon emissions at “Company A”, a producer of high chrome irons (27% chromium) and stainless steels. Using the carbon scope methodology to account for CO_2 emissions, this study should inform the foundry’s strategy to reduce emissions by targeting critical Scope 1 and Scope 2 sources that could be readily addressed, while also providing recommendations for mitigating Scope 3 emissions.

2. METHODOLOGY

This research paper presents a case study conducted in a South African cast iron/high-alloy foundry, and follows the methodology shown in Figure 2. It serves as a foundational example of applying the CO_2 emissions classification methodology (Scopes 1, 2, and 3) in a foundry setting to quantify greenhouse gas (GHG) emissions and to identify opportunities to reduce them. The study focuses specifically on selected processes in this foundry and does not cover the full range of metal casting operations. However, the methodology and findings could be extended and adapted for use in other casting processes.

The proposed methodology, termed the carbon scope framework, is inspired by the techno-economic and environmental (TEE) assessment developed by Ali *et al.*, which quantified carbon emissions in German cast iron foundries, and is informed by other relevant carbon footprint methodologies. It follows a three-stage approach: (1) a literature review to identify CO_2-intensive processes, materials, and mitigation potentials in cast iron production; (2) calculation of the carbon footprint for the relevant alloy production using established emission factors and guidelines; and (3) an economic and environmental assessment of the identified mitigation measures [5]. The life cycle assessment (LCA) and energy assessment conducted by Salonitis *et al.* in the automotive aluminium casting industry serve as a guide for pinpointing critical casting processes that contribute significantly to CO_2 emissions, ensuring that the carbon scope framework is grounded in established practice [6]. Furthermore, the United States Environmental Protection Agency (EPA) provides guidelines and conversion factors for the CO_2 accounting of scope 1, 2, and 3 emissions [9].

Figure 2: Carbon scope methodology

2.1. Data recording

The data collected were provided directly by the casting plants for one year, for January to December 2023. The data set included targeted information on process-specific emissions, particularly those associated with high-temperature operations such as metal melting, which is a major contributor to direct emissions because of its intensive energy requirements. Ladle preheating, typically done using gas burners, also contributes significantly to fuel-based emissions. These direct emissions are documented as part of Scope 1 emissions. The foundries also provided electricity and fuel bills, which were used to estimate Scope 2 emissions from purchased energy. This comprehensive data allowed for a detailed classification and quantification of CO_2 emissions by the foundry's operations, enabling a better understanding of its carbon footprint.

2.2. Calculation of CO_2 emissions fractions using conversion factors

In this part of the methodology, the identified source and the recorded amount of fuel, gas, and electricity used were converted into the volume of CO_2 using conversion factors.

2.2.1. CO_2 conversion factor from South Africa's 2021 grid emission factors report

For this study, the national generation grid emissions factor (NGGEF) was selected as the most suitable and reliable conversion metric for estimating carbon emissions from electricity consumption in the cast iron foundry. Provided by the South African Department of Forestry, Fisheries and the Environment, the NGGEF reflects up-to-date and nationally recognised data, making it a dependable source for emissions calculations. It specifically accounts for emissions at the point of end-user electricity consumption, aligning closely with the energy usage profile of foundries. Using the NGGEF value of 0.985 tCO_2 per MWh, carbon emissions from electricity can be accurately calculated [10].

For example, if a foundry consumed 500 MWh of electricity in a year, the resulting Scope 2 greenhouse gas emissions would be:

$$\text{Scope 2 GHG emissions} = \text{electricity purchased} \times \text{NGGEF} \quad (1)$$

Scope 2 GHG emissions = 500 MWh × 0.985 tCO_2/MWh = 492.5 tCO_2-eq [10]

2.2.2. Greenhouse gas equivalencies calculator

The United States (US) Environmental Protection Agency (EPA) provides a greenhouse gas equivalencies calculator, which was used in this study to estimate the CO_2 emissions from the foundry. This tool helps to convert energy use or emissions data into CO_2, and shows what that amount means in everyday terms, such as the emissions from cars or homes. It makes it easier to understand and explain the impact of emissions and supports efforts to set and share goals to reduce greenhouse gases.

Diesel conversion equation (gallon of diesel)

This conversion factor is approved by the EPA and the US Department of Transportation. A conversion factor of 10.180 grams of CO_2 is used for every gallon of diesel consumed [11]. The conversion equation is provided below:

1 litre of diesel x 0.264172 gallons/l (unit conversion factor) x 10.180 × 10-3 metric tons CO_2/gallon of diesel (CO_2 conversion factor) (2)

Natural gas conversion equation (1000 cubic feet)

Carbon dioxide emissions per therm are calculated by first converting million British thermal units (MMBtu) into therms, then multiplying that by the carbon coefficient, the fraction oxidised, and the molecular weight ratio of carbon dioxide to carbon (44/12) [11]. The conversion equation is shown below:

1 cubic metre of Sasol gas x 0.0353147 Mcf/m3 (unit conversion) x 0.0548 metric tons CO_2/Mcf (CO_2 conversion factor) (3)

Petrol/gasoline consumption

This conversion factor is approved by the EPA and the US Department of Transportation. A standard value of 8.887 grams of CO_2 is emitted for every gallon of gasoline burned. This number is based on the fuel's heat content and assumes that all the carbon in the gasoline turns into CO_2 when burned [11]. The conversion equation is provided below:

1 litre of petrol x 0.264172 gallons/l (unit conversion factor) x 8.887 × 10^{-3} metric tons CO_2/gallon of gasoline (CO_2 conversion factor) (4)

2.3. Identifying Scope 1, 2, and 3 emissions in the context of a South African cast iron foundry

The data recorded in the local foundry was classified under Scope 1, 2, and 3 emissions. Scope 1 emissions were direct greenhouse gas emissions that occurred from sources owned or controlled by the foundry. These included emissions from the combustion of fossil fuels in furnaces, cupolas, on-site generators, and company-owned vehicles, as well as emissions from chemical reactions during metal melting or binder curing processes [12].

Scope 2 emissions were indirect emissions from the generation of purchased electricity consumed by the foundry. Since many foundries rely on grid electricity, often derived from coal in South Africa, these emissions were significant, and were tied to the energy-intensive melting and production operations [12].

Scope 3 emissions were all other indirect emissions that occur because of the foundry's activities but that were not directly owned or controlled by the foundry. It is important to note that the Scope 3 emissions could be difficult to identify because they arose from indirect activities related to the core metal casting process and so were beyond the foundry's direct control. These included emissions from suppliers, product use, transportation, waste disposal, and more. The complexity of supply chains, lack of access to reliable data, and the need to rely on estimates and assumptions made accurate measurement difficult. In addition, with limited regulatory pressure and lower perceived responsibility, many companies struggle to track these emissions consistently [13].

3. RESULTS AND DISCUSSION

This section discusses the results of the study.

3.1. Database source of the process with emission

Table 3 compiles the data recorded from different processes in the foundry, including electricity used in the melting section, gas used to heat up the ladle, diesel used in the plant, and diesel used to deliver cast components, based on the tons of metal that were melted. In general, according to Table 3, higher metal production months corresponded with increased electricity and fuel usage, indicating a link between production volume and energy consumption. There were noticeable fluctuations during the year, with peaks in both production and energy use around May to September, and lower values at the beginning and end of the year. For example, in May, 160 tons of metal were melted using 164,367 kWh of electricity and 1,384.7 litres of diesel, while in January, 43 tons were melted using 45,912 kWh and 943.2 litres of diesel. Electricity consumption per ton melted ranged roughly between 1,020 and 1,120 kWh, showing some variation in energy efficiency month by month.

Table 3: Record of electricity usage and fuel and gas consumption

Period	Tons melted	Electricity consumption KWh	Sasol gas consumption m^3	Staff petrol litres	Deliveries diesel litres	Internal forklift diesel litres
2023/01	43	45912	6794	327.00	301.20	642.00
2023/02	122	128329	10533	305.30	555.60	1,664.80
2023/03	62	66140	8139	333.40	725.90	652.40
2023/04	77	78997	8995	368.50	379.70	720.50
2023/05	160	164367	9104	472.70	562.00	822.70
2023/06	90	94593	10194	400.10	491.80	800.00
2023/07	138	142268	13365	257.70	545.70	1,141.10
2023/08	132	138178	11713	208.40	675.40	1,535.20
2023/09	133	136924	12360	358.40	789.80	1,160.90
2023/10	111	116540	10871	348.20	790.10	1,329.60
2023/11	115	119321	12489	305.80	716.00	1,461.10
2023/12	25	28049	5296	325.90	191.40	546.80

3.2. Converting energy and fuel to CO_2 emissions volumes

This section describes the conversion of Energy and fuel into tons of CO_2 emissions using the NGGEF and the greenhouse gas equivalencies calculator.

Figure 3 shows the converted CO_2 tons of each category of energy usage in the foundry. The table presents the data on CO_2 emissions (in tonnes) from various sources in an industrial or commercial operation, likely collected in different periods or from different operational units. The emissions were categorised into five sources: electricity, gas, staff petrol usage, diesel for deliveries, and diesel used by internal forklifts.

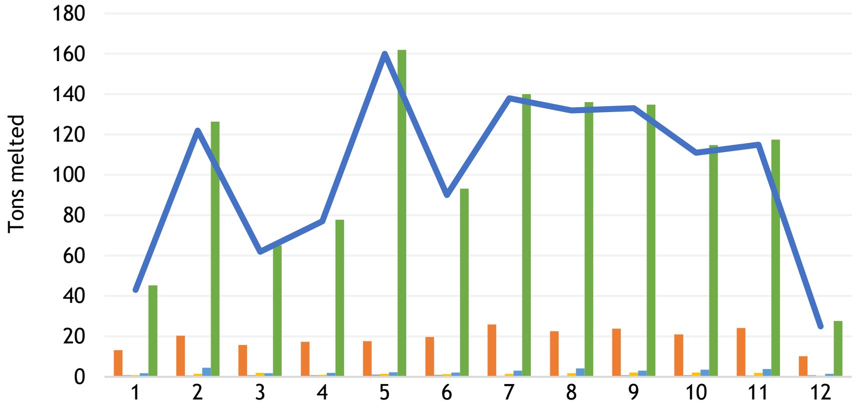
The electricity-related CO_2 emissions showed the most significant variation, ranging from 27.6 tonnes to 161.9 tonnes. This indicated substantial differences in electricity usage, possibly because of changes in production volumes, seasonal variations, or energy efficiency measures during the recorded periods. Electricity was the largest single contributor to CO_2 emissions in most entries, highlighting it as a critical area for emission reduction strategies.

Gas CO_2 emissions, on the other hand, were more consistent, varying between 10.25 tonnes and 25.86 tonnes. This consistency suggests that gas was likely used for essential operations such as heating or process energy, with relatively stable consumption during the period that was studied.

The CO_2 emissions from staff petrol usage were the lowest among the five categories, typically staying below 1.11 tonnes. This reflected either minimal staff vehicle use or high fuel efficiency. While not a major contributor, this category could still be optimised through carpooling incentives or shifts to electric vehicles.

Deliveries using diesel produced between 0.51 and 2.12 tonnes of CO_2, showing moderate variation. This implied a logistical operation that changed in scale depending on business activity. Similarly, internal forklift diesel emissions ranged from 1.47 to 4.48 tonnes, with higher values indicating intensive material handling operations in certain periods.

Overall, the data illustrates that electricity and gas were the dominant sources of CO_2 emissions in this operation, with internal logistics also playing a significant role. Understanding these patterns would be crucial for developing targeted carbon reduction strategies, whether through energy efficiency upgrades, alternative fuels, or improved operational planning.



	1	2	3	4	5	6	7	8	9	10	11	12
Gas CO_2 (t)	13,15	20,38	15,75	17,41	17,62	19,73	25,86	22,67	23,92	21,04	24,17	10,25
Staff petrol CO_2 (t)	0,77	0,72	0,78	0,87	1,11	0,94	0,61	0,49	0,84	0,82	0,72	0,77
Deliveries diesel CO_2 (t)	0,81	1,49	1,95	1,02	1,51	1,32	1,47	1,82	2,12	2,12	1,93	0,51
Internal forklift diesel CO_2 (t)	1,73	4,48	1,75	1,94	2,21	2,15	3,07	4,13	3,12	3,58	3,93	1,47
Electricity CO_2 (t)	45,22	126,4	65,15	77,81	161,9	93,17	140,1	136,1	134,8	114,7	117,5	27,63
Tons melted	43	122	62	77	160	90	138	132	133	111	115	25

Figure 3: CO_2 conversion of energy and fuel

3.2.1. Correlations

Figure 4 illustrates the correlations between the number of tons of molten metal and the consumption of various energy sources, specifically: electricity (R^2 = 0.99), gas (R^2 = 0.65), internal diesel use (R^2 = 0.43), diesel used for deliveries (R^2 = 0.41), and petrol (R^2 = 0.00).

The data clearly shows a very strong correlation between electricity consumption and the melting process. With an R^2 value of 0.99, electricity usage increased almost proportionally with the amount of metal melted, indicating that electricity was the primary energy input for melting operations, likely from electric arc or induction furnaces.

In contrast, gas consumption showed a moderate correlation (R^2 = 0.65) with the amount of metal melted. This suggests that gas was not directly used in the melting process itself but played a supporting role, such as heating ladles or maintaining preheat temperatures, which still scaled somewhat with production but less consistently than electricity.

Diesel consumption, both internally (e.g., forklifts) and for deliveries, showed a weaker correlation, with R^2 values of 0.43 and 0.41 respectively. This implies that diesel use only partially depended on melting volume and was influenced more by material handling demands or by logistical factors that might vary independently of melting output.

Finally, petrol consumption had no observable correlation ($R^2 = 0.00$) with the amount of metal melted. This indicates that petrol use, likely associated with staff commuting or unrelated company vehicles, remained constant regardless of production levels.

In summary, electricity usage was the most reliable indicator of melting activity, while gas played a secondary, moderately correlated role. Diesel and petrol consumption, however, were less affected by monthly production volumes, reflecting their use in support operations rather than in direct melting processes.

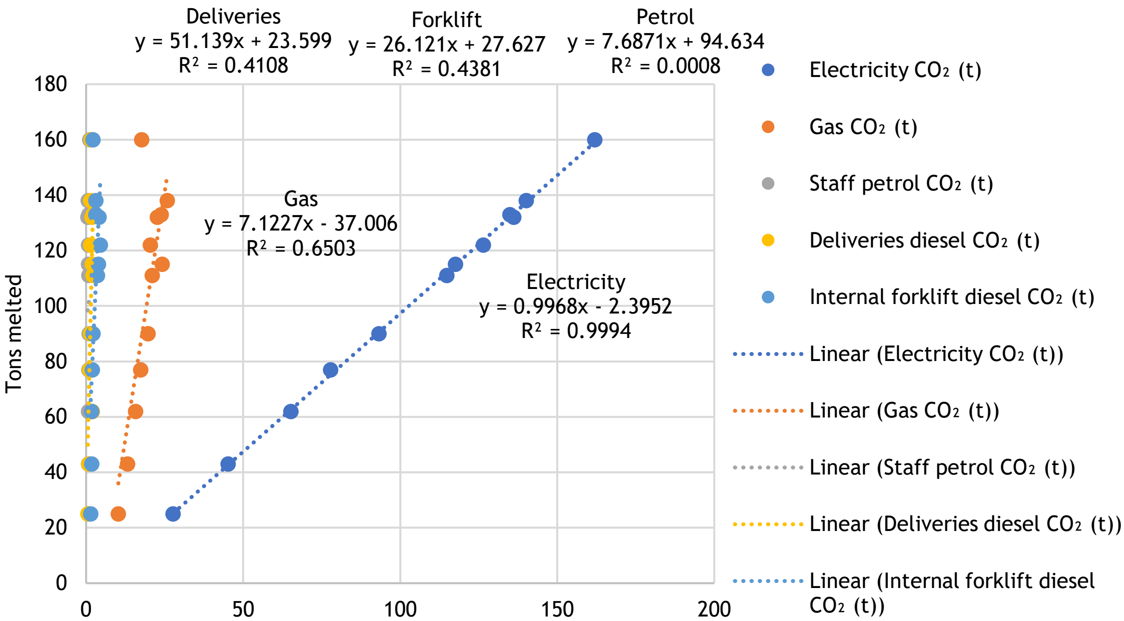


Figure 4: Correlation between Tons of molten metal against Energy and fuel

3.3. Scope classification of CO_2

This section classifies the source of CO_2 according to the carbon scope emissions.

3.3.1. Scope 1 emissions

The use of Sasol gas in the foundry to heat ladles, moulds, or other direct process requirements constitutes a Scope 1 emission because the combustion of gas occurs on-site and results in direct CO_2 emissions from the foundry's own operations.

3.3.2. Scope 2 emissions

Electricity usage falls under Scope 2 emissions. Since the foundry does not directly emit CO_2 from electricity use, the emissions occur off-site at the electricity generation source. Thus, the CO_2 is considered indirect, but still attributable to the foundry's operations.

3.3.3. Scope 3 emissions

Petrol and diesel consumption, specifically the fuel used for deliveries, forklifts, and employee transport, is categorised as Scope 3 emissions. These are indirect emissions that result from activities external to the core metal casting process in the foundry; however, they occur because of its operations. For example, diesel used in delivering finished castings is part of the downstream logistics chain, while fuel used by employees to commute or by contractors, forms part of the upstream or operational support activities. While not emitted on-site, these emissions are still linked to the overall carbon footprint of the metal casting process, particularly in the production of high-alloy castings.

3.4. Recommendations

This section of the results provides key recommendations.

3.4.1. Scope 1: Direct emissions (Sasol gas used for heating ladles and moulds)

To reduce Scope 1 emissions, the foundry should consider upgrading to more efficient gas-fired systems for heating ladles and moulds. Modern burners and preheating systems can significantly lower gas consumption by operating at higher thermal efficiencies. In addition, implementing heat recovery solutions could allow the facility to capture and reuse waste heat from furnaces or ladles that would otherwise be lost, thereby reducing the need for extra fuel. Exploring low-carbon alternative fuels such as biogas, hydrogen-enriched natural gas, or syngas derived from organic waste could cut direct emissions further. Moreover, automating temperature control through sensors and smart systems could help to maintain optimal process temperatures, ensuring that gas is used only when necessary and not wasted because of overheating [1].

3.4.2. Scope 2: Indirect emissions from electricity use

To address Scope 2 emissions, the foundry should invest in energy-efficient melting technologies such as upgraded electric arc or induction furnaces, which use less power per ton of metal melted. According to Salonitis et al., scrap is better than pig iron because scrap metal has already been refined. This means it requires much less energy to re-melt, while pig iron needs much higher temperatures to break down its structure and remove impurities. In addition, higher-calorific coal is better than ordinary coal because it releases more energy per kilogram. This means the furnace needs less fuel overall to reach the required melting temperature, leading to lower total energy consumption. A standard cast iron alloy usually contains up to 20% pig iron, which is associated with high GHG emissions during the production process. According to studies conducted in German foundries, it was discovered that the use of steel scrap instead of pig iron reduces CO_2 emissions by 25%. This is a significant reduction; therefore, replacing pig iron with steel scrap should be pursued to reduce Scope 1 emissions [5][6]

Installing solar photovoltaic systems on the premises would be another effective step, allowing the foundry to generate part of its electricity from renewable sources and thereby reducing its reliance on the grid. For the electricity that must still be purchased, the foundry could negotiate green power contracts with utility providers to source certified renewable energy. Implementing an energy management system would also be beneficial. Rasmeni et al. conducted studies on the topic of energy efficiency, which is relevant to the present study, and explained the benefit of the solution: it can track energy usage in real time, identify inefficiencies, and enable informed decisions that optimise electricity consumption throughout the plant [14].

3.4.3. Scope 3: Other indirect emissions (petrol and diesel spent for deliveries and employee transport)

Scope 3 emissions could be reduced by improving logistical efficiency and transitioning to cleaner transport options. The foundry should use route optimisation tools to minimise the distances travelled during deliveries, reducing diesel use and emissions. Internal transport equipment, such as forklifts, could be replaced with electric models to eliminate on-site diesel consumption. To reduce emissions further, the company could encourage sustainable commuting among employees by promoting carpooling, public transportation, or cycling, and supporting this with infrastructure such as bike racks or subsidised bus. Finally, working collaboratively with suppliers and logistics partners to choose greener transportation options and sourcing materials from closer locations could help to reduce emissions associated with the broader supply chain [15].

3.4.4. Future work

The correlations identified in this study are primarily linear and well explained within the current framework. However, it is recommended that future research explore different forms of dynamics and potential non-linear relationships between variables, which might provide a more comprehensive understanding of the system. Employing density plots to visualise the distribution of conversion factors could uncover hidden patterns or complex causal links not evident through linear correlation analysis alone. In addition, the formulation of a co-occurrence table using software such as RStudio would facilitate a more detailed examination of variable interactions and co-dependencies, potentially reveal new insights, and improve the robustness of the model.

4. CONCLUSION

This work has broader implications for research, policy, and carbon emissions reduction in the metal casting sector. From a research perspective, the proposed carbon scope framework provides a robust foundation for future studies that aim to develop more precise carbon footprint models that are tailored to foundry operations, encouraging interdisciplinary collaboration to innovate low-carbon technologies. In relation to policy making, the identification of key emission hotspots and mitigation potentials could offer valuable insights for policymakers to design targeted regulations, incentives, and carbon pricing mechanisms specific to this industry, thereby supporting national climate action plans. Moreover, by prioritising high-impact emission reduction opportunities, the framework should enable industry stakeholders to allocate resources efficiently to cleaner technologies and energy-efficient practices, advancing the sector's transition towards sustainability. Collectively, these implications should contribute meaningfully to national and international efforts to meet climate commitments and to drive decarbonisation in this critical industrial sector.

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