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A bespoke carbon footprint framework to set the path towards Net Zero in foundries

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Abstract

A bespoke carbon footprint framework for the metal casting industry is presented to enable swifter carbon accounting of foundries and identify energy and carbon footprint hotspots to support the drive towards Net Zero goals. Many manufacturing enterprises in the United Kingdom and Europe are already struggling to maintain financial competitiveness as well as drive towards a sustainable shift, particularly SMEs. This framework is to help alleviate the pressure on the industry by providing an outside tool to direct companies to sustainable solutions. This paper validates such framework breaking down the environmental footprint of ferrous products through energy and material profiles of sand casting processes in two real UK foundries identified as “A” and “B”. During environmental visits, it was established that Foundry A emitted an average of 41700 tons of CO₂ annually and Foundry B 1400 tons. The framework developed to estimate the melting process energy (to be, then, converted into carbon footprint) predicted with about 15% accuracy the actual data. Furthermore, the framework can be expanded and improved on for its accuracy and into other processes within the casting process including melting, core and mould making, pouring sand reclamation, ancillaries and fettling.

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1. Introduction

The drive to Net Zero involves almost every industry and person on the planet. Regardless of the specific sector, if it is left unchanged, then the world is in danger of missing the target to limit to 1.5°C average global temperature increase set by world leaders during the Paris Agreement [1]. Foundation industries, which cover a wide range of fundamental raw materials, such as metals, ceramics, cement, paper, chemicals, and glass contribute 75% of the total UK materials [2]. Metal is a fundamental material to all industries, yet it is manufactured in several different ways. One of these is casting, which is one of the oldest metal-forming methods. Metal casting is regarded

as an energy-intensive industry and a significant contributor to the global carbon footprint [3]. Several different metals can be cast (with ferrous and aluminium-based the most significant in terms of volume), yet according to the International Energy Association (IEA) both steel and aluminium casting industries are growing in demand, steel contributes to 8% of the global energy demand and 7% of energy-related CO₂ emissions, whereas aluminium about 3% of global industrial CO₂ emissions [4,5]. In 2017 basic metal casting in the UK contributed to 817500 tCO₂ with UK aluminium production set at 475900 tonnes [6,7].

Metal casting is a highly established practice with metallic recipes and processes practised on a global scale, yet a precise

breakdown of all the processes and their attributed embodied and operational emissions and energy is disjointed within the literature. Metal casting is formed of several stages that are all vitally important to casting parts, these include melting, core and mould making, sand reclamation, heat treatment, post-process machining, fettling, ancillaries, and others [8]. Of these steps, melting is by far the most energy-intensive, often accounting for more than 50% of the total energy demand of the facility [8,9]. Hence, innovation has focused on refining furnace energy efficiencies and the development of appropriate metrics capable to capture inefficiencies and take steps to increase the relevant environmental sustainability [9].

The foundry industry is caught in an environmental conundrum as it has a higher contribution to emissions and materials with high embodied emissions such as inoculants and pig iron, yet it supplies a significant number of parts for the renewable energy sector, uses a significant amount of scrap metal to close the recycling loop, [3]. Further, tackling the emissions within the casting industry is complicated by the numerous SMEs within the industry. Breaking down emissions within any manufacturing plant is a cumulation of several stages and, although the melting phase has the greatest energy demand and therefore energy-related emissions, embodied emissions of materials and consumables such as sand potentially have a greater carbon footprint than the operational footprint.

This paper aims to demonstrate the basis of a framework based on a universal model for foundries to be validated with a UK focus. Each process stage is modelled through first-order equations to provide a theoretical value for emissions based on different casting methods and equipment to produce a carbon value of a facility and compare this number to the actual carbon footprint. The idea is to break down the environmental footprint of each stage within the casting process, both embodied energy, CO₂e and process energy and CO₂e. To maintain a manageable scope, ferrous metals are the focus of this study, produced through sand casting only. The framework is to help identify the areas of peak emissions within each facility to drive Net Zero goals for foundries of all sizes. The preliminary model and framework are to be validated within two UK foundries that cast iron and steel respectively.

2. Methodology

2.1. Framework modelling

The framework consists of three sections, a process flow chart that maps the entire factory process with inputs and outputs, combined with the background theory and calculations, backed up by a materials database to predict operational and embodied energy usage and carbon emissions. The final section involves the visualisation of the outputs through graphical images with a front-end user interface for the framework to be used in different sand-casting settings with varying data sets.

The framework is initially set up for a range of ferrous metals and alloys using different types of sand-casting routes, to maintain a workable scope. Additionally, the current capability of the framework can only predict energy and CO₂

emissions for the melting stage of the process. The future aim is to expand the framework to incorporate non-ferrous and other casting methods. Furthermore, a Life Cycle Analysis “cradle-to-gate” perspective was utilized with the “gate” being taken to fettling only, with no heat treatment or post-cast machining evaluated within the framework.

From a high-level perspective, sand casting foundries follow a linear production path of melting, treatment, pouring, solidification, shake-out and fettling. Additional value-adding processes such as the core shop, moulding and sand reclamation processes were included, but are yet to be modelled through theory and were taken as a percentage output as advised by the foundry management. To estimate material, energy, and CO₂e, equations were matched to the process flow diagram, incorporating an array of different melting technologies, metal treatment, sand mould types, core-making methods, sand reclamation and fettling methods, ancillaries, and materials. Raw data was collected through a combination of site visits, interviews with experts and literature research.

The process flow diagram enabled each of the high-level stages to be broken down into specific energy use stations.

- Melting: Furnace melting, heating of holding or treatment ladle, treatment processes, metal testing, pouring, and cooling line.
- Core shop: Core sand mixing, oven treatment, resin mixing.
- Sand preparation and moulding: Sand mixing, gassing stations, moulding.
- Sand reclamation: Shake out, separation, sand cooling, centrifugation, gas blowing, thermal reclamation,
- Fettling: Band saws, disc cutters
- Ancillaries: Extraction fans, cranes, forklifts

For all stages apart from melting energy was calculated through, operation time t in hours, machine power consumption (P_c), efficiency factors (ϵ) and material throughput were collected and used to calculate each stage's total energy output as per equation (1):

$$E \text{ (MJ)} = P_c \times t \times \epsilon \times 3.6 \quad (1)$$

For Foundry A total energy per cast metal was provided whereas, Foundry B provided purchase and product output in tonnes to determine the annual embodied energy and CO₂e for both metal and sand used pre-casting. Initial embodied energy and CO₂e were equal to the total annual mass of each material, multiplied by the coefficient of embodied energy or CO₂e. Embodied energy and CO₂e data coefficients were extracted from databases EcoInvent 3 within SimaPro9 or Granta Selector 2021 R1 using EcoInvent v2.2 eco database. The coefficient for silica sand and ferro silicate was sourced from the literature [10,11].

Process energy for melted metal was calculated through a set of equations. Ideal melting energy was calculated through the specific heat capacity (c) of the modal metal cast by the foundry. As a full breakdown of each metal cast with masses within the foundry was not available, it left some variation to the true operational energy to melt the metal. For example, EN GJS 400 18, multiplying the change in temperature from 25°C

(an average shop floor temperature throughout the year even though there is a seasonal fluctuation) to the metal melting point, plus any overheating applied (Δt) as equation 2.

$$E \text{ (MJ)} = c \times \Delta t \times \varepsilon \times 3.6 \quad (2)$$

If the furnace was already charged, the model has an input to incorporate the charge temperature for change in temperature, whereas there are instances such as a Monday morning where the core will have almost solidified and delta T is much larger. Foundries vary dramatically in terms of their casting materials and process, furnace sizes, types, and batches. Melting energy was expanded upon by assuming the furnace as a perfect cylinder or as a perfect cuboid, calculating the maximum metal loading as a factor along with the estimated diameter and height of the furnace to determine the conductive heat loss and how many annual melts would be required for the annual metal melted.

Using the conductive surface area of the cylinder or cuboid surfaces the database allows a selection of refractory materials and thicknesses to be input to estimate the conductive heat loss. The model in this scenario assumes that refractory material is of equal thickness throughout, conductive heat loss only occurs up to the point of filling, is a single material and the efficiency remains constant throughout its life. The conductive heat loss from here is calculated based on the time it takes to melt the number of annual melts which is provided by the factory operators and the size of the furnace against the annual melted material.

Radiation heat loss through the top of the furnace is also accounted for through the top surface area of the furnace cylinder or cuboid. An optional lid is input to the system lined with a refractory material at a set thickness. The time the lid is on or off is input based on the site visits and discussions with operators. The emissivity of molten metal was taken between 0.3 for molten metal based on literature and metal melted although exact values for every metal could not be provided. True convective currents and heat loss are complex systems to model so to provide some degree of heat loss radiation only was utilised.

The sum of the ideal energy to melt the metal, and the conductive and radiation heat loss was used to estimate the total energy used in a facility during melting. The final addition to the melted metal energy was the furnace type and efficiency or fuel efficiency for providing energy. In the UK most furnaces are induction with only a couple of cupolas still in operation at some of the larger casting companies. For electric-based furnaces only an efficiency factor is provided to the total energy sum to provide a final melting energy value. In contrast, for coke or gas-powered furnaces, the calculated energy value is equated to the amount of fuel required to produce that amount of energy based upon the fuel energy density [12]. Finally, any cupola furnaces require the input of limestone which is also accounted for within the model.

This approach provides the basis of the model for metal melting and is to be expanded upon with future iterations to modify the accuracy of production and allow the calculation of other processes such as core making and sand reclamation. For this paper the focus is on the melting stage for both foundries observed and the accuracy and ability of the model. The user interface and output visualisations are not directly discussed herein.

3. Results and Discussion

3.1. Data collection

To populate the model with accurate inputs and validate the model's accuracy, visits to two UK sand casting foundries were conducted, (Foundry A and B). Foundry A focused on ductile iron, whilst Foundry B manufactured a variety of steels. Due to an incomplete data set provided by both foundries, Foundry A data was collected partially from the site visit as well as extrapolated from early energy reports, meanwhile, Foundry B data was provided at a high level with an energy percentage split between the different processes and average material quantities purchased. Other materials such as sodium silicate, sand and steel ratios were taken from the literature [13]. The level of data supplied did not enable a full breakdown of individual components at each stage therefore the only area that could be validated was the melting hence a more detailed and robust model was produced.

From the limited data provided it was understood the calculated total shipped metal for Foundry A was 6448 metric tons of material whilst Foundry B shipped up to 176 metric tons of product. These were calculated from a provided yield for both Foundry A and B and Foundry A's specific energy consumption, which is not disclosed for confidentiality reasons. An estimated total and sub-process operational energy and CO₂ breakdown was determined for each foundry. Both sites use electrical energy as the only energy source within the facility having cut natural gas a few years ago to boost their environmental rating. Melting was done through induction furnaces. Foundry A operated a heavily automated casting line enabling a higher production volume whereas Foundry B was all hand-cast bespoke parts.

3.2. Process energy and CO₂ emissions

From the site visits, Foundry A had a much higher environmental footprint due to the volume of shipped metal, Fig 1 and Fig 2 outline the total process energy and CO₂e breaking down each stage. Most of the energy usage was derived from the melting of the metal which aligns with previous studies [3,8,9]. Other operational sub-processes within the melting category such as treatment, pouring and metal testing were found negligible in comparison to the process energy used in the melting stage. Neither facility housed a holding ladle or treatment ladle, therefore, energy was solely due to melting. Foundry A process CO₂e was significantly higher not just because of the metal melted but also due to excess emissions from magnesium oxide. Most of this waste solidified upon cooling yet it was visually observed a significant proportion would be released into the filtering extractor fans. For Foundry A the second and third most energy-intensive processes were its sand reclamation process which will drive the input embodied energy and emissions down, followed by its automated moulding line and core making. In comparison to Foundry B there is a much smaller amount of energy and emissions and their second and third highest contributors are their auxiliaries, mostly in the form of extraction fans and 3D printing of their patterns or cores. There

was a stark difference in the total annual operational energy between the two foundries. Foundry A was equal to 60500 GJ compared with 996 GJ at Foundry B. Converted into emissions based upon the annual average UK CO₂e/MJ of electrical energy in 2023 equated to 11700 tons of CO₂e for Foundry A compared with 190 tons CO₂e for Foundry B.

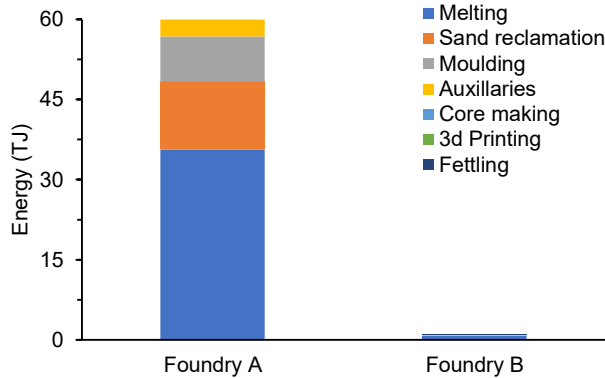


Fig. 1: Annual process energy used within different foundries.

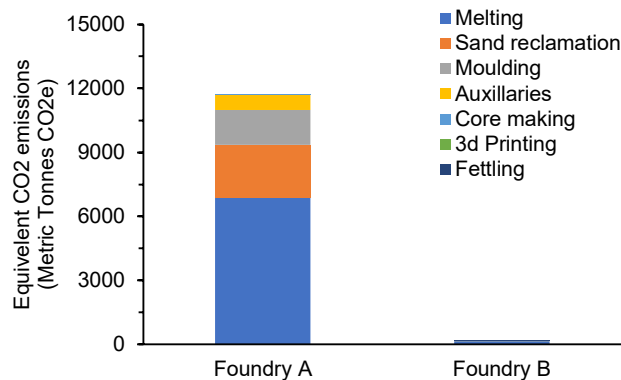


Fig. 2: Annual process CO₂e converted from energy.

To provide a comparative study on the two foundries' environmental performance, both carbon and energy footprints were normalized per shipped metal, for confidentiality reasons the yields of each facility are not disclosed although foundry B had a 45% lower yield. Foundry A produced significantly more castings than Foundry B hence their initial annual energy and emissions were much higher. When normalized the proportion between the two drops dramatically identifying the combination of the yield drop and increased environmental footprint between Foundry A and B as per Fig. 3 and 4.

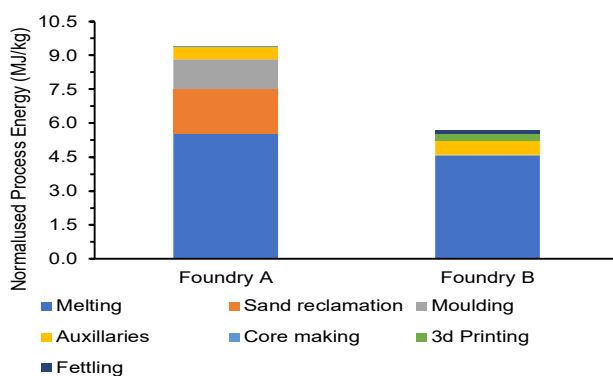


Fig. 3: Normalized annual process energy by the annual shipped tonnage.

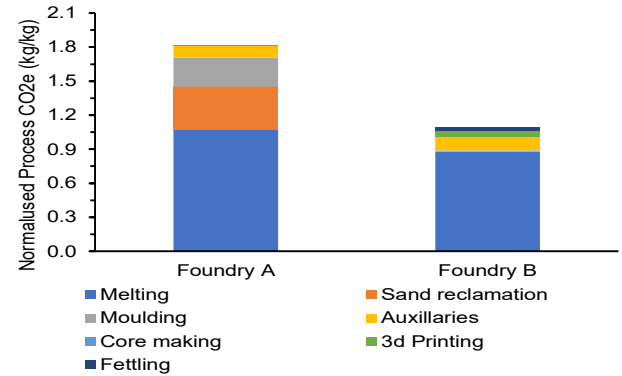


Fig. 4: Normalized annual process emissions by the annual shipped tonnage.

The results find that per ton of shipped metal, Foundry A used 9.39 GJ of energy and emitted 1.81 tons of CO₂e whereas Foundry B required 5.68 GJ and emitted 1.10 tons of CO₂e. The results displayed indicate process savings can still be made in Foundry A and Foundry B has a much lower specific energy consumption even with a lower yield.

3.3. Embodied energy and emissions from inputs

To understand the full environmental impact of a process the input materials need to be accounted for in terms of their prior embodied energy and CO₂e needs to be considered. Materials input at stages of melting, sand processing and core-making were collated and had their embodied values determined. Fig. 5. and 6. represent the embodied energy and CO₂e respectively showing a similar trend to the operational values. Melting held the highest proportion of energy and carbon impact in both cases, with Foundry A having much greater values for both due to the volume output, at an input energy value of 218 TJ and 16172 tons of CO₂e compared with Foundry B energy and CO₂e of 16.5 TJ and 1235 tons. In both cases, sand processing followed melting as the next contributor to the input energy and carbon footprint although both core and sand are almost negligible compared to melting.

Although Foundry A has a significantly higher embodied energy and CO₂e footprint, due to the fact they use a proportion of recycled materials as raw materials, either through recycled scrap steel at various grades or returned parts that don't pass quality checks and a sand reclamation process, they manage their initial potential emissions at a much lower value than without these processes as the energy and CO₂e would increase

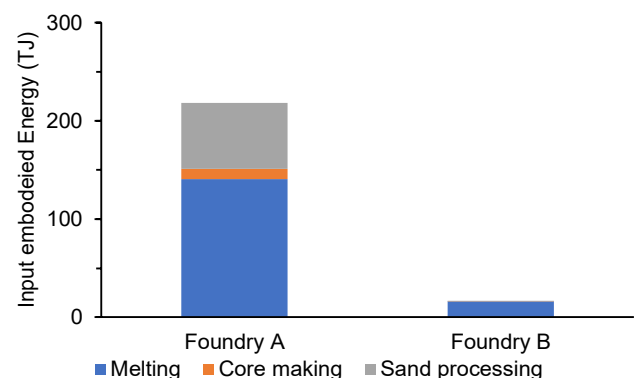


Fig. 5: Annual initial energy footprint of materials brought into the foundry.

by 63% to values of 423 TJ and 31067 tons respectively. However, this strengthens the argument by Jolly that if only the required amount of metal could be melted either by improving yields or melting the exact required amount of material, then the overall process would become cleaner and greener [9].

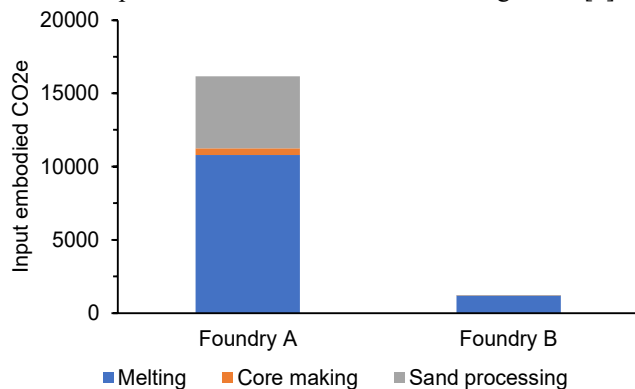


Fig. 6: Annual initial CO₂e footprint brought into the foundry.

Even though Foundry B has a much lower yield, uses virgin steel in almost every process due to customer requirements and no sand reclamation process so virgin silica sand every time, as their annual material output is so much lower it is much further from the values of Foundry A.

To draw comparisons to site efficiencies the data was normalized with shipped metal product. As displayed in Fig. 7. and 8. in this scenario, it finds the trend flips with Foundry B having energy and CO₂e per ton of shipped product equal 94 GJ/ton and 7 ton/ton, the majority of which is due to the metal itself. Whereas Foundry A finds values for energy and

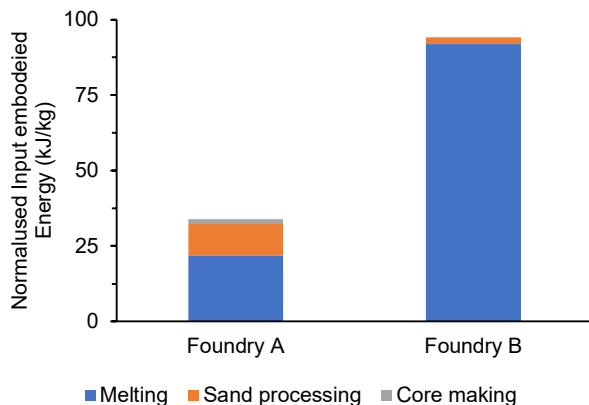


Fig. 7: Annual initial energy footprint brought into the foundry normalized by the annual shipped product tonnage.

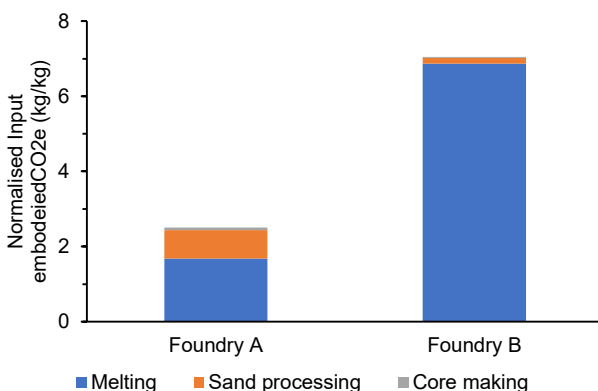


Fig. 8: Annual initial CO₂e footprint brought into the foundry normalized by the annual shipped product tonnage.

carbon footprint of 33.8GJ/ ton and 2.5 ton/ton respectively.

To provide a full picture of both foundries the normalised input material and process energy and CO₂e emissions were combined to provide a clear understanding of the entire plant. It finds that metal melting remains the main contributor to energy and carbon footprint. Similarly, Foundry B has a larger environmental footprint at 100 GJ/ton compared with Foundry A per shipped product tonnage at 43 GJ/ton and 8.1 ton/ton and 4.3 ton/ton CO₂e for Foundry B and A respectively, as in Fig. 9. and 10. Foundry B could benefit from some further investigation into its process to optimise its emissions more. Improving their yield, use of sand reclamation and the potential of recycling scrap or working as a casting consortium to manage the scrapped material between other foundries could become environmentally beneficial. In both cases, initial material energy and CO₂e have the greatest environmental footprint for both Foundries.

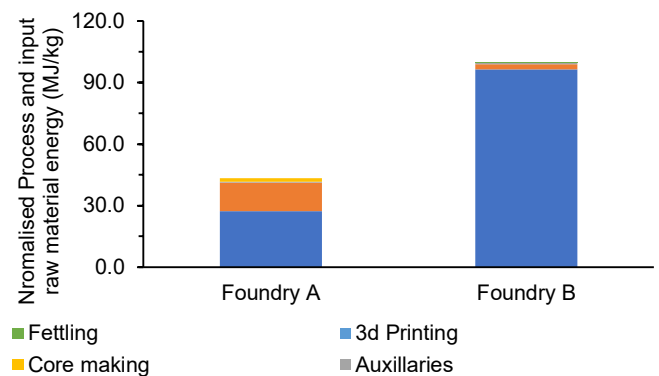


Fig. 9: Normalised energy for the total raw material and process energy for different foundries.

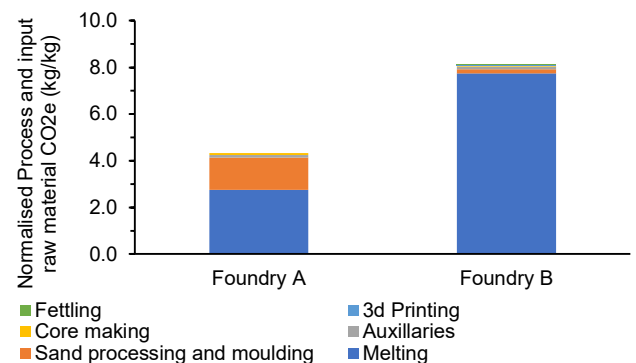


Fig. 10: Normalised CO₂e for the total raw material and process emissions for different foundries

3.4. Model application, limitations, and future work

Having established a high-level environmental overview of the two foundries, the tool was brought in to validate its ability to predict process energy and therefore energy. As the tool was only usable within the melting of metal stage it became convenient this was the highest environmental impacting sector. Foundry A with the larger environmental impact was used to validate the model. Foundry A used an induction furnace for its melting, for this example, EN GJS 600 3 was used as the only material for the prediction of energy. As per the methodology the same melted mass was used provided by the foundry with an average yearly shop floor temperature of 20°C. It was assumed only 4 weeks of closure per year and the

furnace was not in use over weekends or at night and 6 melts per day, therefore an initial charge temperature would have 3 different values of 20°C on Monday mornings, 200°C Tuesday – Friday mornings and then 650°C for all other melts. The furnace was lined with a 400 mm dolomite refractory at a 94% fill capacity and no lid was present. With this established it was calculated that the ideal energy to melt the metal was 2.98TJ. Conductive heat loss through the sides and base of the furnaces was equal to 10.32 TJ whilst the radiation heat loss was 15 TJ. This total led to 37TJ including coil and furnace inefficiencies of 2% and 21% respectively, compared with the provided value of 35.6 TJ. The model was able to predict a current discrepancy of 3.7% which can be improved by addressing several limitations of the model.

Several improvements can be made to the current model to improve the accuracy and the accuracy of the data provided by the foundry including:

- Using a single metal melted is not a true representation as there are over 20 different metals cast at Foundry A yet the one selected was the one cast the most. Similarly, this will also impact the overheating value because the Foundry has a defined set point for different metals and products dependent on the geometries of casting.
- Secondly seasonal average temperature will vary the ideal energy, yet a continual temperature profile was never provided.
- The specific heat capacity was assumed constant as the metal melted when this is only true to a certain temperature.
- The convective heat loss is not accounted for in the model, conductive heat loss only accounts for a single refractory material, thickness and at the maximum temperature.

Incorporating some of these changes along with similar frameworks to be created for the other sectors can drive this as an important Net Zero tool for the metal casting industry, enabling an environmental footprint of all foundries across the world and a route of identifying environmental hotspots or areas that can be overlooked for improvement with fast return on investment. A fully functioning framework can enable sustainability improvement and potential financial rewards to improve their sustainability.

4. Conclusion

The paper discussed a framework to be used as a tool within the ferrous metal sand casting industry to predict energy and carbon footprint. The framework focuses on metal melting both from an operational and embodied perspective to enable the industry to identify hotspots for sustainable solutions to be implemented. Initially, two UK foundries were assessed on their carbon footprint, both operation and initial material footprints identifying that Foundry A had a total carbon footprint of 4.3 and 8.1 ton/ton CO₂e per ton of metal shipped. Following the environmental assessment and confirming that metal had the highest environmental impact the framework was evaluated for its accuracy in predicting Foundry A's melting energy with a discrepancy of 3.7%. The model has been

designed to be easily modified with estimate improvements and should now be extended to other processes within the casting line such as the sand process, core shop, moulding and ancillaries.

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