Assessment of Greenhouse Gas Emissions and Reduction Strategies: A Case Study of Foundry Plant in Thailand

Rungrote Sumarat and Maneerat Khemkao*

Rattanakosin College for Sustainable Energy and Environment, Rajamangala University of Technology Rattanakosin, Nakhon Pathom 73170, Thailand

ABSTRACT

This study aimed to assess the potential greenhouse gas (GHG) emissions from a foundry or metal casting company. The primary sources of emissions used to analyze were the production processes, energy consumption, and associated GHG emissions, focusing on electricity usage from handling raw materials to producing the finished product. Various production units used electricity, including furnaces, casting equipment, and other systems. This process followed the Intergovernmental Panel on Climate Change (IPCC) guidelines and relevant emission factors to calculate the amount of GHG emissions caused by electricity use. Key emission hotspots were identified, and actionable strategies to mitigate its environmental impact through GHG reduction were also proposed. The collected data showed that the average electric power consumption for the entire plant in 2022 and 2023 was 7,503,225 and 6,806,179 kWh, respectively, for the casting product. Foundry plants emitted 3,725,145 and 3,125,480 kg CO_2eq from their electricity consumption in 2022 and 2023, respectively. The average carbon intensity is 0.489 kg/kWh; however, the carbon intensity of iron-casting production varies based on the production process, raw material, and energy mix. It found that induction melting furnaces consumed more electrical power than other production processes, accounting for 71.22% of total electrical power consumption and 67.28% in the plant. Optimizing furnace efficiency and installing a solar rooftop as a captive power plant could reduce the electrical power consumption.

Keyword: Foundry/ Greenhouse gas emission/ Greenhouse gas reduction/ Carbon intensity

1. INTRODUCTION

The urgency of addressing climate change is undeniable. As the world grapples with the increasingly severe impacts of global warming, it's imperative that every industry sector take concrete steps to reduce its greenhouse gas (GHG) emissions. Hannah [1] reports a 73.2% increase in energy usage in electricity, heat, and transport, a 24.2% increase in energy use in industry, and a 7.2% increase in energy-related emissions from the manufacturing of iron and steel. The foundry industry, a key player in the global manufacturing supply chain, is no exception. This research paper examines the potential GHG emissions from foundry, a metal casting company located in Thailand, highlighting the urgent need for sustainable practices within the industry. Foundries, by their very nature, rely heavily on energy-intensive processes. Melting, casting, and finishing operations often involve high temperatures, demanding significant electricity consumption, which in turn translates to significant GHG emissions.

Casting industry is among the weighty CO_2-emitting industrial areas; therefore, every action in the direction of sustainability plays a vital role in carbon emissions reduction Mitterpach [2]. The foundry minimized the overall impact of its main processes on environmental quality by implementing environmental measures, particularly its technological methods. These methods focused on reducing the demand for raw materials and other materials, energy consumption, release of emissions to the atmosphere, water use, and creation and production of solid waste, as well as increasing the quality of drained water.

The implementation of the EU Carbon Border Adjustment Mechanism (CBAM) will significantly impact foundries in Thailand, especially those exporting cast iron to the EU. Here are the key issues that foundries in Thailand will face:

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

1. Increased costs: CBAM will require Thai cast iron to pay an additional carbon tax, resulting in increased production and export costs. Foundries may need to adjust their selling prices to offset the increased costs, which could affect their ability to compete with competitors from other countries.

2. Technical adaptation: Foundries will need to improve their production processes to be more efficient and reduce greenhouse gas emissions. They may need to invest in new technologies, such as energy-efficient smelting, renewable energy, greenhouse gas management, and recycling.

3. Lack of data: To calculate the CBAM carbon tax, detailed greenhouse gas emissions data are required. Foundries in Thailand may not have enough data or the ability to manage it.

4. Future uncertainty: CBAM is still in its infancy and is constantly evolving. Thailand's foundries need to be ready for policy uncertainty, constant change, and ongoing adaptation.

5. Impact on the supply chain: Foundries might need to switch raw material suppliers. Adjusting the manufacturing process to comply with CBAM standards could potentially impact the supply chain and customer relationships.

6. Difficulty in accessing the market: CBAM may be a barrier to exporting cast iron products to the EU, as it may make Thai products more expensive and uncompetitive with products from other countries.

Carbon pricing has recently gained further momentum from the European Union's (EU) plan for the Carbon Border Adjustment Mechanism (CBAM). The CBAM aims to align the greenhouse gas (GHG) emission costs in imported products with those within the EU [3]. Among these strategies, the considers carbon pricing to be a cost-effective way to achieve emission reductions.

This research paper takes a comprehensive approach to assess the GHG emissions of a foundry and proposes actionable actions to reduce them. The study analyzes the company’s manufacturing processes, energy consumption data, and associated GHG emissions, focusing on electricity consumption as the primary source of emissions. This analysis helps identify key GHG emission hotspots, leading to the development of targeted strategies to reduce the foundry’s environmental impact. The research uses the Intergovernmental Panel on Climate Change (IPCC) guidelines and associated emission factors to quantify GHG emissions associated with electricity consumption, providing a starting point for the foundry to use as input and guidance in implementing its actions concerning the European CBAM.

2. METHODOLOGY

2.1 Collection plant information

This research adopts a comprehensive approach to assess GHG emissions at a foundry plant in Nakhon-Pathom, Thailand. The study utilizes data from the company's operational records, encompassing a detailed examination of the production processes, energy consumption patterns, and subsequent GHG emissions. The data collections comprise the electrical power consumption of the entire plant and the electrical power consumption of melting furnaces for the years 2022 and 2023 (Table 1).

2.2 Production process analysis

The research delves into the intricate steps involved in metal casting, from the initial raw material handling to the final finished product. This meticulous analysis aims to identify the specific GHG emission sources inherent in each stage of the production process. The process diagram is created comprehensively with the resources for sand mold and core making. The diagram indicates the resource used for iron melting. The diagram can assist in an overview of plant resources, processes, waste, and GHG emissions for finding out the solution of GHG reduction.

This research meticulously analyzes the electricity usage across various production units, including furnaces, casting equipment, and auxiliary systems. The data collection involves compiling detailed records of electricity consumption across all operational areas of the foundry plant.

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

Table 1. Electricity consumption for each production process.

Process	Electricity consumption (kWh)		Process	Electricity consumption (kWh)	
	2022	2023		2022	2023
Core making	23,370	22,755	Molding	212,515	206,923
Shakeout	77,216	75,148	Air compressor	597,911	582,177
Sand preparation and mixer	638,134	621,341	Dust collection system	157,263	153,125
Melting furnaces	5,343,960	4,579,142	Cooling tower	75,468	73,482
Shotblast	66,880	65,120	Grinding	208,278	202,797

2.3. GHG emission calculation

The Intergovernmental Panel on Climate Change (IPCC) guidelines and relevant emission factors to quantify GHG emissions associated with electricity usage were utilized. This rigorous approach ensures accurate and reliable calculation of GHG emissions based on established international standards. The emission factor is considered based on the last update by IPCC 2013 GWP 100a V1.03 on the Thai National LCI Database, TIIS-MTEC-NSTDA (with TGO electricity 2016-2018). The GHG emissions of electricity consumption on each process are calculated by Eq (1):

$$\text{GHG (kgCO}_2\text{e)} = \text{Electricity Consumption (kWh)} \times \text{Emission factor (kgCO}_2\text{e/kWh)} \quad (1)$$

3. RESULTS

3.1 Metal casting process

Fig. 1 depicts the metal casting process. There are 8 processes:

1) The core-making process involves machines that have both electricity and gas options. The machine uses gas to heat the filling until it hardens. To remove moisture, the filling in an electric oven was heated.

2) The sand preparation process involves machine-feeding the metal product into the foundry sand after separating it from the mold. Next, sand was extracted, sorted by size, and assessed for strength to transform it into foundry sand. Sand mixer, where sand will mix with various binders once it possesses the appropriate properties. Various binders, such as sea sand, bentonite, starch, resin, etc., are based on the suitability and properties of the casting sand required.

3) The molding process involves the machine utilizing the necessary patterns to create the desired mold shape. A pattern plate mounts the patterns. A sand supply system provides the machine with mixed molding sand and a binder. The machine automatically places a layer of sand onto the pattern plate. A compaction mechanism, such as a vibrating table or a pressing action, compresses the sand around the patterns to achieve the required mold strength. After compacting the sand, we form the top half of the mold. We bring the two halves of the mold together and press them into one complete mold. Next, we finish the sand mold and prepare it for the next step.

4) The metal melting process involves adding metals and additives to the raw material of each type of cast iron in the furnace. The alloys include silicon, pig iron, carbon, silicon carbide, manganese, sulfur, fire-cutting iron, and other substances such as inoculant, magnesium, and redux brick, which are used to adjust the quality of the metal. The temperature of metal melting in the induction furnace has to be increased up to 1,550 °C.

5) The pouring process, where workers scoop up the melted iron with a small ladle and pour it into the sand mold. An automatic machine initiates a second process, which involves pouring the melted iron into the mold. This process cools both the sand and the casting products. Before entering the sand separation process, the iron-poured sand mold moves on a track and cools down with air.

6) Shakeout, in which a vibrator separates the sand from the casting metal. Next, the vibrator transports the sand to the sand mill preparation process, where it becomes the new casting mold. The casting metal is subjected to a variety of processes, including shot blasting, blasting, and metal grinding.

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

7) Sand blast/shotblast, where a machine applies sandblasting or metal pellets to the casting surface to remove sand, improve the metal surface, remove burrs and sharp edges, increase strength, and create pressure on the surface.

8) Grinding process, where the worker grinds some cast iron on an automatic grinding machine to remove the edges of the metal surface once more.

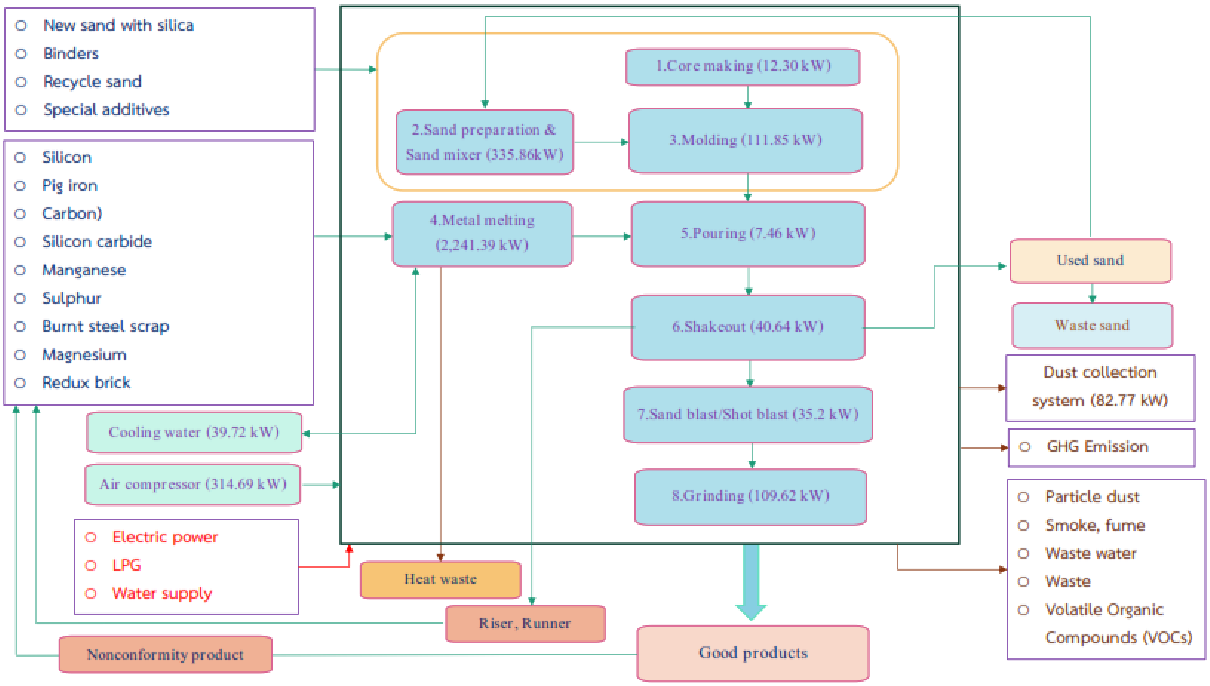

Figure 1. Flow diagram for metal casting process.

The foundry's annual production of cast iron products (Fig. 2a) in 2022 and 2023 was 651,550 and 587,500 kg, respectively, which varied from 487 to 747 tons for 2022 and 503.5 to 636 tons for 2023. In 2022 and 2023, March and January had the highest product capacity, while December and April had the lowest. In 2022 and 2023, the total product was 7,752 and 6,866.6 tons, respectively. It was observed a direct variation in electricity consumption with production. The plant's average electricity consumption was 640,644.10 kWh/month in 2022 and 580,183.30 kWh/month in 2023 (Fig. 2b). The peak load electricity consumption for 2022 was 694,319.40 kWh in March, and for 2023 it was 615,603.00 kWh in July. Therefore, the energy consumption for 1 kg of product varied between 0.915-1.091 kg/kWh in 2022 and 0.986-1.1.035 kg/kWh in 2023.

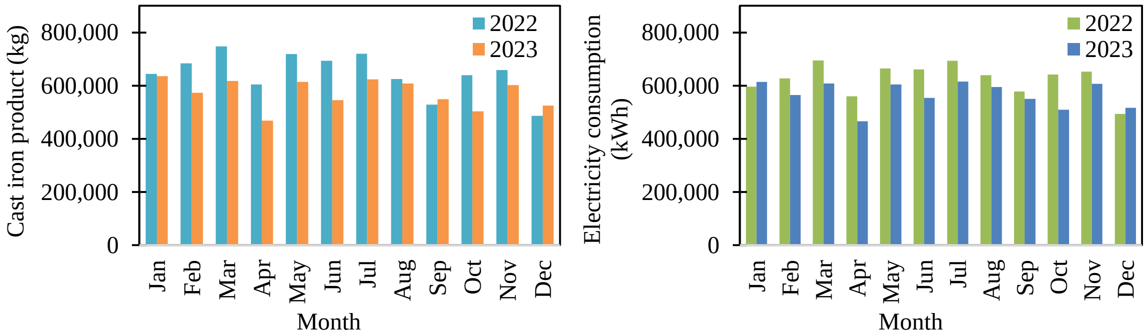

Figure 2. Annual data for metal casting products (left) and (b) electricity consumption (right).

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

3.2 GHG emission from electricity consumption

The amount of electricity used significantly contributes to its overall carbon footprint. The plant's electricity consumption from the casting metal process in Fig. 2 resulted in GHG emissions of 3,750.87 tons CO_2e and 3,402.41 tons CO_2e for 2022 and 2023, respectively (Fig. 3). The entire plant's average carbon intensity is 0.489 kg CO_2e/kWh.

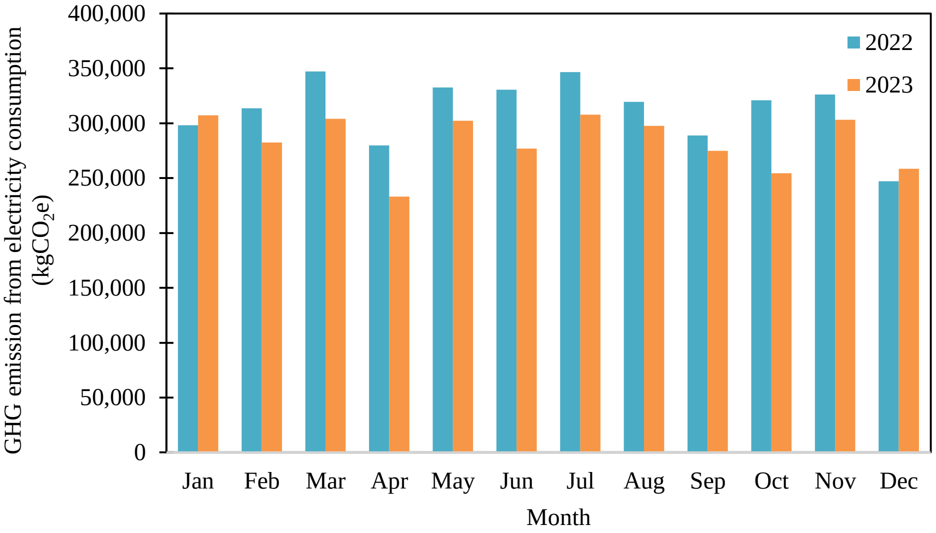

Figure 3. GHG emission from electricity consumption of metal casting process.

4. DISCUSSION

4.1 Carbon intensity

It is essential to note that the carbon intensity of iron casting production is dynamic and varies based on factors such as the production process, raw materials, and energy mix. Induction melting furnaces, due to their high energy demands, exhibit a higher carbon intensity than other production processes. In 2022, induction furnaces accounted for 71.22% of the plant's total electricity consumption, increasing to 67.28% in 2023. According to Sirintip [4], the CO_2 intensity of semi-finished steel products was 0.44 tCO_2e/ton, whereas the CO_2 intensity of finished steel products was 0.17 tCO_2e/ton.

4.2 Key emission hotspots

The research identified three key emission hotspots within Foundry's operations. Electricity consumption is consistent with production. To consider the electricity reduction potential relating to GHG emissions, in the other manufacturing processes except for induction furnaces, electricity is mainly supplied to motors in machines such as belt conveyors, sand mixer machines, shot blasting machine molding machines, oscillating machines, bucket elevators, induced draft fans (ID fans), grinding machine, etc. that are not too high in electricity power consumption.

4.2.1 Electric furnaces

Induction furnaces, crucial for melting metal, consume a substantial amount of electricity, contributing significantly to GHG emissions. The electrical power consumption of induction melting furnaces was higher than other production processes; they were 71.22% in 2022 and 67.28% in 2023 of total electrical power consumption in the plant. The most energy-intensive process is metal melting, whether in an induction furnace or a cold or hot blast cupola.

The process is intrinsically inefficient due to the high temperatures of approximately 1500 °C. Depending on whether the melting occurs in an induction furnace or a blast cupola, two different strategies need to be considered. Adopt the correct feedstock conditions, prevent overheating, and operate at the maximum power input level in the former optimization processes. A well-insulated lid

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

can reduce heat losses; the furnace coils must be duly cooled at a temperature of 40-45 °C that allows a heat recovery useful only for building heating via low temperature terminals or for DHW. The best measure to improve efficiency in blast cupolas is to pre-heat the combustion air, which requires suitable heat exchangers that can withstand both temperature and corrosion. According to Lazzarin [5], the high temperature of the flue gas enables the powering of both steam direct cycles (Rankine) and the easier activation of ORCs, even after the air combustion pre-heating process.

4.2.2 Casting equipment

The various casting processes, which include sand mixing, equipment transportation by belt conveyor, core making, and molding machines, significantly contribute to the foundry process and increase GHG emissions.

Recycling waste foundry sand in the construction industry would save a lot of resources [2]. Composite technologies enable energy savings of approximately 8.92% and 6.99% per unit casting, in both single small batch and batch casting manufacturing processes. Although casting has a similar energy efficiency to additive manufacturing, the time consumption per unit is much lower, which has significant application value. Compared to traditional casting methods, composite technologies save 6.99% energy in mass production, reduce 11.06% carbon emissions, and save 5.571 h in manufacturing per unit casting [6].

4.2.3 Auxiliary systems

Supporting equipment, including pumps, compressors, and air conditioning units, also contributes to energy consumption and GHG emissions, albeit to a lesser extent than the furnaces and casting operations. The Cooling Dry Air (CDA) system in the fab was classified as a two-pressure level system using a heated-type dryer. Compared to the original data, the highest energy savings for the CDA system was 3,050 MWh. That is, the CDA system's energy consumption decreased by 8.17%. This energy savings constituted 1.81% of the overall energy consumption of the fab [7].

4.3 GHG reduction strategies

Based on the identified emission hotspots, the study proposes actionable strategies to reduce GHG emissions at Foundry with the Energy Efficiency Improvements Approach (EEIA).

4.3.1 Furnace optimization

Implementing modern, energy-efficient furnaces with advanced control systems can significantly reduce electricity consumption during melting operations.

The IMF achieves the melting temperature of iron at about 1250 °C. The molten metal temperature is further raised to 1450 °C to compensate for the transfer and pouring heat losses. Apart from this, heat is lost as radiation from weekly insulated portions such as the IMF coil cradle assembly, ladle, and tundish attached to the CCM. Good quality thermal insulation should limit the external temperature of these surfaces to a maximum of 65 °C. The thermal imaging technique was used to study the radiation heat losses from various surfaces. The process of tapping molten metal, transporting it in a ladle, and pouring it into a casting primarily results in heat loss. Reduce the transit time to cut down on heat loss from radiation during the process [8].

The model predictions and real-time melting showed a good correlation between 81% and 95% when parameter fitting techniques were used on the measured operational data of the induction furnaces at different times of melting. Effective material balancing and controlled charge can reduce energy consumption by comparing the mass composition of a current molten bath and melting time. Onigbajumo [9] observed the melting time as a function of the molten bath's elemental charge composition and the overall scrap material charge.

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

4.3.2 Casting process optimization

Optimizing casting cycles and implementing energy-saving techniques can help to reduce electricity consumption. When the pouring station is located far from the furnace, the design of the casting process impacts energy consumption and operating time. This is due to the need to raise the iron temperature to compensate for the decrease in melt iron temperature on the way to the pouring station. This, in turn, prolongs the furnace operation, leading to an increase in GHG emissions. Three types of sand-casting carbon source models were built by three categories of process design parameters analysis of sand mold casting. so as to predict the carbon emission of sand mold casting. The feasibility of the proposed method for estimating the carbon emission in the process design stage was validated by using a practical example. Hu [6] demonstrated a significant decrease in carbon emissions through the comparison of two process design schemes based on this method.

4.3.3 Motor efficiency

Upgrading motors and pumps to higher-efficiency models can minimize energy waste and contribute to a more sustainable operation. The benefits of using IE3 motors extend beyond these cost savings on energy bills and include a return on investment. Furthermore, investing in high-efficiency motors not only reduces operating costs, improves reliability, and achieves long-term financial sustainability, but also contributes to the energy conservation and sustainability goals of businesses and industries [8].

4.3.4 Solar photovoltaic (PV) system

Installing 1,547.83 m^2 of photovoltaic PV solar cells on the roof results in a total power output of 700.92 kWp. It will be installed together with a 6-unit 90 kW inverter at latitude 13.7275 and longitude 100.2904. Tests conducted revealed an average global output of 5.1 ay $kWh/m^2/day$ on a tilted plane. The plant has received the electric power generation from the photovoltaic PV solar cells. The investment in this PV solar installation will pay back within 4 years.

Raksakulkarn [10] conducted a study on 45 industrial estates, identifying a total area of 94,126 rai. This area represents a potential roof area for installing solar rooftops, with a total installed capacity of 1421.05 MW, which equates to a GHG reduction potential of 0.95 $MtCO_2e$. The level 2 assessment of the GHG reduction potential from all aerial photographs shows that the industrial estates and IEAT head office have a total roof area of 38,222,516 square meters. Of this, 5,452,726 square meters have solar rooftops installed, while the remaining roof area is 32,769,790 square meters without solar rooftops. The potential roof area for installing solar rooftops is 6,553,958 square meters, representing a total installed capacity of 773.02 MW, which represents 0.52 $MtCO_2e$ of GHG reduction potential [10].

4.3.5 Waste management and recycling

Implementing a comprehensive recycling program for scrap metal, sand, and other materials can minimize waste, reduce the need for raw material extraction, and decrease GHG emissions associated with material production. Mining and smelting of ores provide the raw materials for iron smelting. The process of obtaining raw iron and raw materials for steel production generates a significant amount of greenhouse gas emissions.

Casting aluminum with 100% primary material causes more global warming than cast iron, but using 60% secondary material reduces the impact compared to cast iron with 80% primary and 20% secondary material [11].

Abdelshafy [12] found that the smelting process and renewable energies play a role in decreasing the carbon footprint. In terms of the input materials, the results demonstrate that increasing the steel scrap content achieves significant reductions in CO_2 emissions. An alloy composition with a 25% steel scrap content leads to a minimum carbon footprint of 650 kg CO_2e/ton. The amount of steel scrap directly affects the amount of CO_2 emissions. When a cast component uses more steel scrap, it leaves less primary metal to fill it. Since the mining of metal ore emits CO_2, recycling metal scrap positively

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

impacts carbon emission control by preventing the extraction of new metal. According to one ton of steel scrap used, it protects the environment from 1.5 tons of CO_2 emissions [13].

4.3.6 Waste heat recovery

Utilizing waste heat from furnaces for preheating or other processes can improve energy efficiency and minimize reliance on external heat sources, such as the pre-heating of the ladle, the pre-heating of another induction furnace located nearby before melting the iron, and the pre-heating of the sand core in the core-making process. These comprehensive strategies, if implemented effectively, have the potential to significantly reduce Foundry's environmental footprint and contribute to a more sustainable future for the company and the broader manufacturing industry.

The foundries waste more than 50% of their energy on melting the raw materials, which then solidify in sand molds. Muthuraman [14] suggested that the heat released during molten metal solidification is used to preheat the raw materials. Durgesh [11] found that the heat-recovery capacity varied depending on the insulation of the raw materials and the water moisture content in the casting sand.

4.4 Dust collection systems

Different factors such as particle characteristics, flue gas, temperature, fine or coarse, abrasive, sickly or non-sickly, cost, and efficiency can influence the selection of air emission control equipment in a foundry. Typically, foundries utilize four types of dedusting technology:

1) Filter bags are ideal for capturing small dust particles, 0.2–0.5 μm, but they are not suitable for capturing particles with high humidity and heat.

2) Wet scrubbers were applied for capturing particles with corrosive properties and high heat resistance (0.1–1.0 μm) and spray scrubbers for dust larger than 5 μm.

3) Cyclone was installed for capturing large dust of 15–40 μm, not suitable for capturing particles smaller than 10 μm.

4) An electrostatic precipitator is not suitable for capturing sticky dust but is effective in capturing particles smaller than 1 μm.

Dust control technologies involve installing bag filters and cyclones to regulate emissions from melting processes. Wet scrubbers capture water-soluble compounds like sulfur dioxide (SO_2) and chlorides. The adoption of cyclones as pretreatments and use of bag filters typically enables emission levels of 10 mg/Nm^3 or less. The large amount of sand used in lost mold casting generates dust emissions during the various molding stages and produces on-metallic particulates, metallic oxide particulates, and metallic iron.

Casting, shakeout, and finishing processes emit non-metallic particulates. The prevention and control techniques for particulate matter arising from casting and molding include installing dry dust collection technologies, such as bag filters and cyclones, instead of wet scrubbers, particularly in green sand preparation plants. Dry techniques facilitate the simple collection, transportation, and recirculation of dust in the sand mixing process, thereby preventing the production of effluent from wet scrubbers. Casting and finishing shops, in particular, use filters on exhausts; while molding and casting shops employ vacuum cleaning.

It was recommended to install closed dedusting units in working areas [15] and [16]. Since shotblasting and grinding produce similar particulates, a filter bag is a suitable tool for these processes. However, emission control devices, such as the dedusting system, are not appropriate for controlling or reducing greenhouse gas emissions. In addition, Skoromny et al. [17] recommended to simply scale up the dust collection system by replacing several low-capacity collectors with one general-capacity collector. Energy consumption at the collector manufacturing stage reduced 3–10 times and ensured a significant reduction in operation energy consumption of the dust collector during its service life.

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*Corresponding Author: Maneerat Khemkhao
E-mail address: maneerat.khe@rmutr.ac.th

5. CONCLUSIONS

The average electric power consumption for the entire plant in 2022 and 2023 was 640,644 and 580,138 kWh, respectively, for the casting product. They emitted 3,725,145 and 3,125,480 kg CO_2eq from their electricity consumption in 2022 and 2023, respectively. The average carbon intensity is 0.489 kg/kWh. The electricity consumption, particularly for melting and casting processes, is the primary source of GHG emissions at the foundry. While the company's annual production of cast iron products varied, the reliance on electricity for these processes results in substantial CO_2 emissions. Strategies for GHG emission reduction include optimizing furnace efficiency, utilizing modern and advanced control systems, implementing energy-saving techniques during casting processes, and upgrading to higher-efficiency motors and pumps. Installing a solar rooftop as a captive power plant could significantly reduce electricity consumption from the grid, thereby decreasing the company's overall carbon footprint. By implementing strategic and comprehensive GHG reduction plans, foundries can not only reduce their environmental impact but also enhance their competitiveness and achieve a sustainable future.

Recommendations:

- To quantify energy consumption and identify specific areas for improvement, conduct a detailed energy audit.
- Develop a comprehensive GHG reduction plan incorporating the proposed strategies. Implement a robust monitoring and evaluation system to track progress toward reduction targets.
- Reduced Raw Material Use: Recycling steel scrap reduces the need for virgin iron ore mining and processing, which are energy-intensive and produce significant GHG emissions. By using scrap, foundries can decrease the demand for new raw materials.

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*Corresponding Author: Maneerat Khemkhao
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