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Carbon Emissions Quantification from Ceramic Tile Production by Using Life-Cycle Assessment (LCA): A Case Study of PT Sinar Karya Duta Abadi, Indonesia

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ABSTRACT

A major environmental problem in the ceramic tile industry is pollution in the form of carbon emissions from energy-intensive production. The study set out to measure how much carbon is released throughout the ceramic tile production chain and to pinpoint which steps contribute the most. It also explored a few grounded options for cutting those emissions, especially in stages where energy use tends to spike. A cradle-to-gate LCA was carried out assuming a functional unit of 1 m^2 ceramic tile, with primary data extracted from the corporate information for January-December 2024. The system boundary primarily focuses on gate-to-gate processes, while upstream raw material extraction was incorporated through secondary data (emission factors) rather than direct system modelling. According to the LCA results, the carbon footprint of ceramic tile production was estimated at 7.3401 kg $CO_{2\text{-eq}}/m^2$, with fuel combustion and electricity consumption dominating the impact, contributing 67.29% and 30.60% of total emissions, respectively. Sensitivity analysis confirmed that overall emissions are primarily driven by energy-related inputs, particularly kiln fuel use. Based on these findings, two mitigation scenarios were assessed. The installation of a waste heat recovery (WHR) system reduced emissions by 10.09%, while its combination with partial substitution of natural gas by biogas and hydrogen-enriched

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fuel increased the reduction potential to 17.16%. Life cycle cost analysis further demonstrated the economic feasibility of both options, yielding negative abatement costs of -82.53 USD/t CO_2 for the WHR scenario and -17.50 USD/t CO_2 for the combined scenario, indicating that meaningful emission reductions can be achieved alongside long-term cost benefits.

Keywords: Ceramic tile production, emissions, environmental impact, Indonesia, life cycle assessment

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INTRODUCTION

The world of the ceramic tile industry is a strange one within the construction sector. Tiles are valued because they stand up to traffic, present an intentional and clean appearance in a finished space, and generally don't put materials costs beyond the range of a budget (Chouhan et al., 2024). But even the comfort of familiar surfaces rests on a production chain that links back to hot, mineral-mining intensive kilns and continued dependence on fossil fuels. In many other plants, firing and drying lines operate for almost 365 days a year, using large amounts of electricity and fuel such as natural gas (Ancona et al., 2023). These energy requirements build up the environmental profile of the sector and raise questions more generally about whether it is feasible for a material being widely used to be incorporated into attempts to combat climate change (Xian et al., 2024).

In a world where the industry behaved more sensibly, ceramic processing would run on tightly controlled feeds, recover most of the heat it now wastes and monitor its emissions closely enough to make at least some recommendations about what should come next (Delpech et al., 2017). In reality, things rarely fall into such neat order. Previous research suggests that the global warming potential (GWP) of ceramic tiles can reach 133.60 kg $CO_{2\text{-eq}}/m^2$, with over 90% stemming from CO_2 emissions during natural gas use and raw material processing. The firing stage takes up a disproportionate share of the burden and can easily send the global warming potential of a single square meter of ceramic tile far past the levels commonly documented for many other construction materials (Ibáñez-Forés et al., 2011; Vieira et al., 2023). Temperatures regularly exceeding 1000 °C make meaningful energy savings difficult unless the entire production setup is rethought. Many plants still depend on older machinery that was never built for low-carbon goals, so the gap between what is possible and what actually happens remains quite large (Yuan et al., 2024).

Many researchers have tried to close this gap by digging into process tweaks (comparisons of firing/fuel options) (Wang et al., 2020), running careful evaluations of kiln performance (Ros-Dosdá et al., 2018b), or tracing emissions from the earliest raw-material steps up to the factory gate (Bovea et al., 2007). These attempts have some valuable findings, although they usually concentrate on individual production stages, certain furnace kinds or clusters of plants in Europe and East Asia (Ibáñez-Forés et al., 2011; Ye et al., 2018). As such, the larger picture remains imprecise. Downstream emissions are indirectly taken into account in many works, or facility-specific aspects affecting results, such as the regional fuel mix and/or the local clay mineralogy, are not considered (Cellura et al., 2011). When that information isn't on offer, there is a real problem. It can also be the case that its determinates a baseline against which emissions reduction needs to be compared, and its consequences will only become apparent when measures are implemented in locations in which production systems appear very differently from those presupposed by global datasets (Fernández-Miguel et al., 2022). And by those places the numbers start to go fuzzy, and there are not, in fact, particularly compelling plans for mitigation where there jolly well should be.

The consequences of this knowledge gap are more sweeping than most people imagine. When emissions data is sparse, companies may overestimate or underestimate what their true carbon liability is. Policymakers thus can create incentives or standards that do not match the real conditions inside factories. Yet not even the architects and developers selecting low-carbon materials are, in practice, able to make fully informed choices (Ibrahim et al., 2024; Suwatno, 2023; Tacconi, 2018). A larger problem is the sparse availability of locally grounded data, which hinders making real progress toward national climate goals. Indonesia illustrates this tension. Despite having a net-zero emission target of 2060, its building sector continues to expand; nevertheless, estimates of the production-stage CO_2 emissions for commonly used construction materials (e.g., ceramic tiles) are surprisingly limited (Bungas et al., 2024; Hermawan & Prabhawati, 2024). Hence, reliable and company-specific LCA investigations are of paramount importance for industrial decarbonization pathways and in reinforcing responsibility for the ceramic tile sector (Ding et al., 2023; Hechelmann et al., 2023; Liu et al., 2023).

A lot of what we know about ceramic tile impacts is still based on studies in places such as Italy, Turkey, Egypt and China, with the firing choices, production approaches and also the clay compositions significantly different from each other (Ali, 2024; Li et al., 2022; Türkmen et al., 2021). Indonesian producers, though, appear only fitfully in the literature, and that absence is significant. Industrial performances vary across Southeast Asia, and many plants in Indonesia use alternative fuels or recycled inputs that are not exactly comparable to global practices (Handaya et al., 2022). With no data from real facilities, any effort to cut emissions will just be based on the uncertain footing of hypotheticals that may have little to do with the realities of production systems in Indonesia. Without data from real facilities, any plan to slash emissions ends up relying on assumptions that may not reflect reality in Indonesia's production systems. In the absence of data from real facilities, any plan to cut emissions winds up resting on assumptions that might not match actual circumstances in Indonesia's production systems.

LCA offers a systematic way of dealing with these uncertainties by following the environmental impacts from the extraction of raw materials to manufacture and distribution.

It applies a procedure that follows ISO 14040 and 14044 (Marson et al., 2024). Currently, LCA is utilised with ceramic tiles to provide industry and policymakers the ability to measure their greenhouse gas (GHG) emissions profiles, as well as pinpoint the production stage in which most of the environmental profile occurs; this allows for discovering possible mitigation strategies that can mitigate carbon footprints (Pini et al., 2014). Used judiciously, LCA also has a habit of illuminating the sources of emissions in reality, like lifting hoods behind which factories rarely peer. By evaluating the actual contributions of all components in production, it closes the gap between efficiencies which engineers draw on paper and the much messier performance that comes out of a factory line (Ferrari et al., 2019; Sappa et al., 2019).

This paper applies a gate-to-gate life cycle assessment (LCA) to PT Sinar Karya Duta Abadi, one of the largest ceramic tile manufacturers in Indonesia. This approach is particularly relevant as it captures emission sources that are directly controllable at the plant level, such as fuel consumption, electricity use, and process-related emissions. By isolating the production phase, the analysis enables a more precise identification of emission hotspots and supports the development of targeted and practically implementable mitigation strategies within industrial operations. Moreover, given the limited availability of facility-specific data in Indonesia, a gate-to-gate perspective provides a robust and context-sensitive basis for evaluating decarbonization opportunities under real operating conditions.

The objective of the study is to quantify CO_2 emissions, identify the most contribute processes within the production system, and develop technically grounded mitigation options under local industrial conditions. In addition to the baseline assessment, the study incorporates sensitivity analysis to evaluate the robustness of the results and to examine the relative influence of key inventory parameters on total emissions. Furthermore, a life cycle cost (LCC) analysis is conducted to assess the economic feasibility of selected emission reduction scenarios, enabling an integrated environmental-economic evaluation. This study specifically examines how the emission profile is shaped by plant-level fuel use, raw material composition, and process configuration, which differ from patterns commonly reported in international studies. The work holds both academic and practical significance, contributing region-specific empirical evidence to LCA research while providing quantitative insights to support industrial decision-making and policy development in the context of increasingly stringent climate and sustainability requirements.

METHODS

Framework

Life cycle assessment based on ISO 14040 and 14044 was carried out to quantify the carbon emissions generated from ceramic tile production in PT Sinar Karya Duta Abadi, Indonesia. The methodological framework is structured with four core phases of

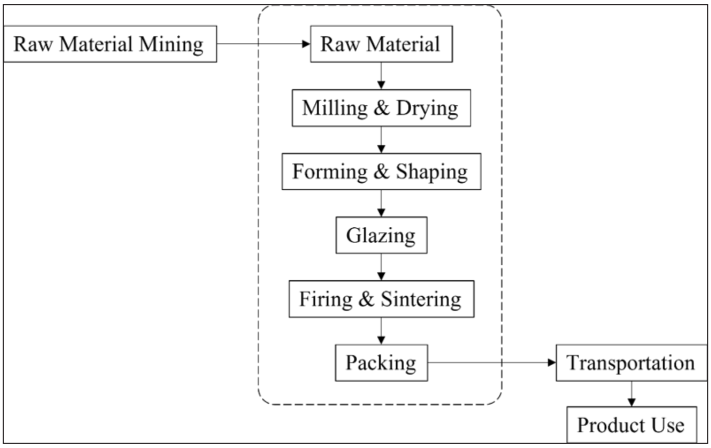

Figure 1. System boundary of ceramic tile production

LCA: goal and scope, life cycle inventory (LCI) analysis, life cycle impact assessment (LCIA) and interpretation, as recommended by standard guidelines for LCA (Vieira et al., 2023). All data collection and modelling were conducted in accordance with gate-to-gate system boundaries to consider emissions associated with on-site production processes, while upstream raw material extraction was incorporated indirectly through secondary emission factors.

Goal and Scope

This study seeks to assess the GWP in $CO_{2\text{-eq}}$ for the production of ceramic tiles in Indonesia from raw material milling and drying through to packing at the factory gate. This study takes a gate-to-gate perspective, as shown in Figure 1. Although the study adopts a gate-to-gate system boundary focusing on on-site manufacturing processes, upstream emissions related to raw material extraction are incorporated indirectly using secondary data (emission factors). Therefore, raw material extraction is not explicitly modelled as part of the foreground system but considered as background data. It is non-comparative and related to the topic of sustainability reporting and carbon-intensive stages. The functional unit is 1 m^2 of ceramic tile (Yuan et al., 2024) and it conforms with the international criterion. That work occurred at PT Sinar Karya Duta Abadi in Indonesia, the type of thing that happens quietly underfoot, for a full year - January through December 2024.

Life Cycle Inventory (LCI)

Our raw data was collected directly on the shop floor of PT Sinar Karya Duta Abadi, where we also performed multiple rounds of walk-throughs and a relatively complete account of the mass and energy flows. The inventory included the usual technical suspects: how much raw material was used; how much fuel was burning or leaking refrigerant, and the plant's electricity load. For upstream data, in particular, emission factors for the extraction of raw materials and electricity use, the project had to depend on literature values and ecoinvent type databases because regional data sets were not broadly available. All LCI numbers applied in this study are presented in Table 1, Table 2, and Table 3.

Table 1
Emission factors of fuel

Emission Source	Emission Factor (ton $CO_{2\text{-eq}}$/TJ)			References
	CO_2	CH_4	N_2O	
Diesel	74.1000	0.0030	0.0006	(Garg & Pulles, 2006)
Natural gases	56.1000	0.0010	0.0001	(Garg & Pulles, 2006)
Gasoline RON 90	69.3000	0.0030	0.0006	(Garg & Pulles, 2006)

Table 2
Emission factor of raw material, refrigerant, and electricity

Emission Source	Emission Factor	References
Dolomite	0.4773 ton $CO_{2\text{-eq}}$./ton carbonate	(Harnisch & Agyeman-Bonsu, 2006)
Calcium carbonate	0.4397 ton $CO_{2\text{-eq}}$./ton carbonate	(Harnisch & Agyeman-Bonsu, 2006)
Barium carbonate	0.2230 ton $CO_{2\text{-eq}}$./ton carbonate	(Harnisch & Agyeman-Bonsu, 2006)
Calcite	0.4397 ton $CO_{2\text{-eq}}$./ton carbonate	(Harnisch & Agyeman-Bonsu, 2006)
Refrigerant R32	0.6500 ton $CO_{2\text{-eq}}$./ton refrigerant	(Szczęśniak & Stefaniak, 2022)
Refrigerant R410A	1.7250 ton $CO_{2\text{-eq}}$./ton refrigerant	(Szczęśniak & Stefaniak, 2022)
Refrigerant R134	1.0000 ton $CO_{2\text{-eq}}$./ton refrigerant	(Szczęśniak & Stefaniak, 2022)
Refrigerant R407C	1.5255 ton $CO_{2\text{-eq}}$./ton refrigerant	(Szczęśniak & Stefaniak, 2022)
Electricity	0.00087 ton $CO_{2\text{-eq}}$/kWh	(Ministry of Energy and Mineral Resources, 2021)

Table 3
Fuel, material, refrigerant, and electricity consumptions

Emission Source	Consumption
Stationary generator (diesel), L	0.0382
Stationary generator (natural gases), MMBTU	2.0268
Mobile combustion (diesel), L	0.3307
Mobile combustion (gasoline), L	0.0092
Dolomite, kg	0.1863
Calcium carbonate, kg	0.2605
Barium carbonate, kg	0.0233
Calcite, kg	9.3501

Table 3 (*continued*)

Emission Source	Consumption
Refrigerant R32, kg	77.9000
Refrigerant R410A, kg	55.3000
Refrigerant R134, kg	22.0000
Refrigerant R407C, kg	20.5000
Electricity, kWh	83.1961

Table 4
Conversion factors of fuel

Fuel	Conversion Factors
Diesel	0.00003868 TJ/L
Natural gases	0.001055 TJ/MMBTU
Gasoline	0.00003466 TJ/L

Life Cycle Impact Assessment (LCIA)

The quantitative impact assessment was conducted by combining primary and secondary inventory data. The work focused only on the climate change impact category, since the main goal was to estimate carbon emissions expressed as GWP. Other categories (acidification, eutrophication, or resource depletion) were ignored.

The carbon emissions generated from energy consumption can be calculated using Equation 1 (Li et al., 2022), where C_e is the carbon emission generated by energy consumption, M_e is the amount of energy consumed, and F_e is the CO_2 emission factor. Energy consumption is calculated by converting the amount of fuel used into terajoules (TJ) using the conversion factors in Table 4.

$$C_e = M_e \times F_e \qquad [1]$$

Carbon released as carbonates break down during high-temperature calcination can be estimated using Equation 2 from (Li et al., 2022). In that equation, C_c represents the emissions tied to the raw materials themselves. M_c is simply the amount of carbonate material that actually gets used, although in practice, this number can vary a bit depending on the batch and how consistently the feedstock is prepared. F_c refers to the emission factor for those carbonate materials, which researchers often treat as a fixed value even though, in reality, different sources of limestone or dolomite can show slight differences in their carbon dioxide output. The emission factors for carbonate decomposition (calcite, dolomite, calcium carbonate, and barium carbonate) were adopted from the 2006 IPCC Guidelines for National Greenhouse Gas Inventories, as reported by Harnisch and Agyeman-Bonsu (2006).

Carbon emissions from refrigerant use are estimated through Equation 3, where C_r represents the emissions produced by the release, M_r is the amount of refrigerant that actually escapes into the air, and F_r is the emission factor that converts that leaked mass into its carbon dioxide equivalent. When Equations 1, 2, and 3 are brought together, they give the overall carbon emissions associated with the ceramic tile life cycle, which is summarised in Equation 4.

$$C_c = M_c \times F_c \qquad [2]$$

$$C_r = M_r \times F_r \qquad [3]$$

$$C = \sum_{e=1}^{k}(M_e \times F_e) + \sum_{c=1}^{n}(M_c \times F_c) + \sum_{r=1}^{m}(M_r \times F_r) \qquad [4]$$

Emission Reduction

The mitigation scenarios were developed based on explicit technical assumptions to ensure transparency and reproducibility. For the WHR scenario, emission reduction was estimated based on the expected thermal recovery efficiency of waste heat recovery systems applied to kiln exhaust gases, which offset a portion of fuel demand. For the combined scenario, partial fuel substitution was modelled using defined blending ratios of biogas and hydrogen-enriched fuel relative to natural gas, along with their respective lower heating values. The detailed parameters and assumptions used in both scenarios are summarised in Table 5.

Table 5
Assumptions for emission reduction scenarios

Scenario	Parameter	Assumed Value	Basic/Justification
WHR	Thermal recovery efficiency	15% effective fuel reduction	Conservative value aligned with the literature range of 8-25% WHR performance in kiln systems
WHR	Heat utilisation application	Preheating of combustion air and raw materials	Standard integration in ceramic roller kiln waste heat recovery systems
WHR	System coverage	Kiln exhaust gases	The main source of thermal loss was identified in the baseline results
Combined scenario	Additional fuel substitution rate	30% reduction of remaining fuel-related emissions	Literature-based conservative assumption for partial substitution in industrial burners
Combined scenario	Biogas fuel type	Renewable biogas (CH_4-rich gas)	Typical substitution fuel in industrial thermal systems
Combined scenario	Biogas lower heating value (LHV)	~20-23 MJ/Nm^3	Standard range for upgraded biogas
Combined scenario	Hydrogen blending ratio	10-20% (volumetric basis)	Conservative blending range for hydrogen-enriched combustion in industrial burners

Table 5 (*continued*)

Scenario	Parameter	Assumed Value	Basic/Justification
Combined scenario	Reference fuel	Natural gas	Baseline kiln fuel in PT Sinar Karya Duta Abadi
Combined scenario	System condition	No change in production output	Consistent with cradle/gate-to-gate LCA assumption in study

Table 6

Data used for life cycle cost assessment

Fuel	Value	Unit
Lifetime	15	Years
Discount rate	8	%
CAPEX – WHR system	1,200,000	USD
CAPEX – Fuel system (biogas + burner retrofit)	600,000	USD
Annual O&M cost – WHR	3	% of CAPEX
Annual O&M cost – fuel system	2	% of CAPEX
Natural gas price	9	USD/GJ
Biogas price	14	USD/GJ
Hydrogen-enriched fuel price	20	USD/GJ
Fuel system price (70% biogas + 30% H2)	6.8	USD/GJ
Emission factor of natural gas	56	kg CO_2/GJ

Life Cycle Cost

The life cycle cost (LCC) analysis was conducted using economic and technical input data summarised in Table 6.

RESULTS AND DISCUSSION

Life Cycle Assessment Result

The life cycle assessment carried out for the ceramic tile production line at PT Sinar Karya Duta Abadi mapped the carbon footprint associated with an annual production output of approximately 14.782 million square meters, representing a large-scale ceramic manufacturing facility operating under Indonesian industrial conditions. Operational data were compiled directly from plant-specific records, including handwritten logs for diesel consumption and refrigerant replenishment, invoice-based records for natural gas and electricity usage, and weighing sheets used in the batching area for raw material inputs. While the level of data uniformity varied across categories, particularly for mobile fuels and refrigerants, site-specific operational data allows the inventory to reflect actual production practices rather than generic or database-derived assumptions, and was therefore considered sufficiently representative of routine plant operations.

Table 7
The carbon emissions of ceramic tile production

Emission Sources	Carbon Emission (kg $CO_{2\text{-eq}}/m^2$)	Total Carbon Emission/year (ton $CO_{2\text{-eq}}$)
Fuel	**4.9394**	**73,019.2563**
Stationary generator (diesel)	0.0101	149.5855
Stationary generator (natural gas)	4.8899	72,286.5541
Mobile combustion (diesel)	0.0386	571.0024
Mobile combustion (gasoline)	0.0008	12.1143
Raw material	**0.1379**	**2,037.7100**
Dolomite	0.0043	64.2821
Calcium carbonate	0.0058	85.1984
Barium carbonate	0.0002	2.3860
Calcite	0.1276	1,885.8461
Refrigerant	**0.0169**	**249.5540**
Refrigerant R32	0.0009	13.3250
Refrigerant R410A	0.0065	95.3925
Refrigerant R134	0.0015	22.0000
Refrigerant R407C	0.0080	118.8365
Electricity	**2.2459**	**33,201.4272**
Total	**7.3401**	**108,507.9500**

Based on the compiled inventory, emission values were calculated for fuel use, electricity consumption, raw materials, and refrigerants. The detailed emission breakdown is presented in Table 7, enabling transparent attribution of emissions to individual input categories. The total carbon footprint of the production phase was estimated at 108,507.95 tons of $CO_{2\text{-eq}}$ per year, providing a quantitative baseline for subsequent scenario evaluation. When normalised to annual production, this corresponds to an emission intensity of 7.3401 kg $CO_{2\text{-eq}}$ per square meter of ceramic tiles produced and the annual production volume of approximately 14.782 million m², confirming the internal consistency of the functional unit scaling across all calculated results.

Carbon emissions were classified into four main sources: fuel consumption, electricity use, raw materials, and refrigerants, allowing clear identification of emission hotspots along the production chain, shown in Figure 2. Fuel consumption emerged as the dominant contributor, accounting for approximately 67.29% of total emissions, equivalent to 73,019.2563 tons of $CO_{2\text{-eq}}$ annually. Within this category, natural gas combustion in stationary kilns accounted for nearly all fuel-related emissions (72,286.5541 tons $CO_{2\text{-eq}}$ per year, or 98.997%), indicating that kiln firing processes remain the primary driver of direct emissions in the assessed production system, while diesel contributed a comparatively minor share.

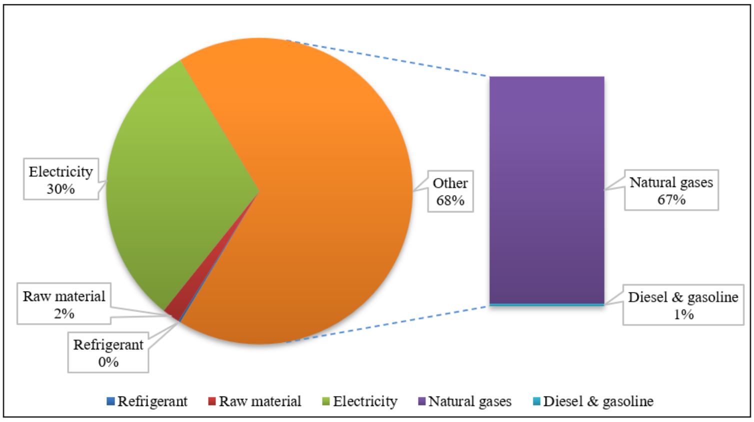

Figure 2. Hierarchical distribution of life cycle carbon emissions from ceramic tile production, highlighting fuel combustion and electricity use as dominant emission hotspots and their detailed contributors

Electricity consumption represented the second-largest emission source, contributing 30.60% of total emissions, or approximately 33,201.4272 tons of $CO_{2\text{-eq}}$ per year. These emissions were associated with purchased electricity used across production processes, including milling, pressing, glazing, and auxiliary operations. The substantial contribution of electricity-related emissions highlights the influence of grid electricity characteristics on the overall carbon footprint of ceramic manufacturing, particularly in regions where fossil-based power generation remains dominant.

Fuel combustion emerged as the dominant contributor primarily due to the high thermal demand of the kiln process, which operates continuously at elevated temperatures and currently does not incorporate heat recovery or preheating systems. In contrast, the emissions associated with purchased electricity are largely influenced by the carbon intensity of the Indonesian electricity grid, which remains dependent on fossil-based generation. Therefore, the higher contribution of fuel reflects both the process characteristics of ceramic firing and the direct dependence on natural gas, whereas electricity-related emissions highlight the indirect effect of the upstream power mix. This distinction suggests that near-term mitigation at the plant level should prioritise kiln efficiency improvements, while deeper reductions in electricity-related emissions will also depend on broader decarbonization of the national power system.

Raw material inputs contributed a smaller fraction of total emissions, amounting to approximately 1.88% (2,037.71 tons $CO_{2\text{-eq}}$ per year). Despite its relatively limited contribution compared to energy-related sources, calcite was identified as the dominant contributor within this category, responsible for 1,885.8461 tons of $CO_{2\text{-eq}}$ annually, accounting for more than 92% of raw-material-related emissions. This finding reflects emissions associated with carbonate decomposition and upstream material processing, which are intrinsic to ceramic body formulation.

Refrigerant-related emissions accounted for 0.23% of the total footprint, corresponding to approximately 249.554 tons of $CO_{2\text{-eq}}$ per year. Although quantitatively small, this category was characterised by high global warming potential values. Among the refrigerants used, R407C and R410A contributed the largest shares, accounting for 47.62% and 38.225% of refrigerant-related emissions, respectively, underscoring the relevance of refrigerant management practices even when total leakage volumes are limited.

Overall, emissions from fuel combustion and electricity consumption (Scope 1 and Scope 2) collectively accounted for approximately 97% of the total carbon footprint. This concentration of emissions within energy-related processes provides a clear and data-driven basis for prioritising mitigation strategies, while also reinforcing the suitability of the assessed system as a case study for evaluating energy-focused emission reduction scenarios in ceramic tile manufacturing.

Studies conducted on Spanish porcelain stoneware reported emission intensities ranging from 130 to 160 kg $CO_{2\text{-eq}}/m^2$ (Ros-Dosdá, Celades, et al. 2018a), while another study reported approximately 133.60 kg $CO_{2\text{-eq}}/m^2$ for glazed stoneware under comparable production conditions (Ibáñez-Forés et al., 2011). Assessments conducted in Turkey reported emission intensities of approximately 14.4-14.5 kg $CO_{2\text{-eq}}/m^2$ (Morfino et al. 2022; Türkmen et al. 2021). The carbon emission intensity of 7.3401 kg $CO_{2\text{-eq}}/m^2$ observed in this study is lower than values reported in several international life cycle assessments of ceramic tile production. This lower value may be attributed to several plant-specific factors, including the kiln configuration, fuel efficiency, operational practices, and the characteristics of the raw material mix used in the studied facility. For example, the plant's production system may exhibit lower thermal losses, more efficient energy utilisation, or a different material formulation compared with facilities reported in previous studies. In addition, variations in system boundary definitions, production scale, and allocation assumptions across studies may also contribute to the observed differences. Therefore, the comparison suggests that emission intensity in ceramic manufacturing is not only influenced by national or regional energy structures, but also by facility-level technical and operational conditions.

In contrast, the emission intensity obtained in this study is closer to values reported for ceramic industries in Brazil and Mexico. Previous study reported emission intensities ranging from 5.07 to 5.31 kg $CO_{2\text{-eq}}/m^2$ for Brazil and 6.00 to 6.33 kg $CO_{2\text{-eq}}/m^2$ for Mexico (Saavedra & Osma, 2025). The proximity of these values suggests that ceramic production systems operating under energy structures dominated by natural gas, with relatively limited electrification of thermal processes, tend to exhibit comparable carbon intensities. These comparisons further indicate that emission intensities in ceramic manufacturing vary widely depending on energy sources, kiln configurations, operational efficiency, and methodological assumptions applied in LCA studies.

Fuel-related emissions dominated the overall footprint, reflecting the inherently energy-intensive nature of high-temperature firing processes in ceramic production. Natural gas-fired kilns, particularly those operating without heat recovery or preheating systems, have consistently been identified as the primary emission hotspot across multiple LCA studies. Similar patterns were reported for Portuguese roof tile production (Quinteiro et al. 2022) and sanitaryware manufacturing (Desole et al. 2024), where kiln firing stages contributed the largest share of environmental burdens. The present findings reinforce the central role of thermal energy demand in shaping the life cycle impacts of ceramic products.

At PT Sinar Karya Duta Abadi, kiln systems are fuelled by natural gas and operate without heat recovery or preheating zones, resulting in substantial thermal losses through exhaust streams. Previous studies, including (Oliveira et al. 2021), have shown that modern roller kilns equipped with waste heat recovery systems can reduce energy consumption by approximately one-fifth, although actual performance is strongly dependent on operational discipline, process control, and maintenance practices. The absence of such systems in the studied facility provides a plausible explanation for the dominance of fuel-related emissions observed in the baseline assessment.

Electricity consumption constituted the second-largest emission source. This trend is consistent with earlier studies, Muthukannan and Chithambar Ganesh (2019) and Wang et al. (2018), which reported elevated electricity-related emissions in production systems involving prolonged drying cycles or high-temperature processes. In the Indonesian context, electricity-related emissions are strongly influenced by the national grid, which remains heavily dependent on coal and natural gas (International Energy Agency, 2024). As a result, improvements in plant-level electrical efficiency alone may have a limited impact unless accompanied by broader decarbonization of the upstream power supply.

Although raw materials contributed a relatively small share of total emissions, calcite dominated this category due to direct CO_2 release during calcination. This finding aligns with previous analyses by a previous study (Mattila et al. 2014), which identified carbonate mineral decomposition as a significant emission source in ceramic manufacturing, even when its associated energy demand is comparatively modest. The result emphasises that process-related emissions, in addition to energy use, should be considered when evaluating mitigation opportunities.

Refrigerant-related emissions accounted for only a minor fraction of the total footprint; however, their high global warming potentials result in disproportionately large climate impacts. R407C and R410A were identified as the main contributors within this category. These findings underscore the importance of improved leak management, regular monitoring, and a gradual transition toward refrigerants with lower climate impacts, particularly as auxiliary systems such as cooling and air conditioning continue to expand in industrial facilities.

Sensitivity Analysis

Sensitivity analysis in LCA is a systematic approach used to examine the extent to which the calculated environmental impacts respond to variations in assumptions, input parameters, and methodological choices. Rather than aiming to modify the numerical results, its primary purpose is to evaluate the robustness and credibility of the conclusions derived from the LCA model. In the present study, sensitivity analysis was performed on the main emission hotspots identified in Figure 2, including fuel consumption (natural gas, diesel, and gasoline), electricity use, raw materials, and refrigerants. These parameters were selected due to their dominant contribution to the overall carbon footprint. The outcomes of the sensitivity analysis are illustrated in Figure 3, providing insight into the relative influence of key inputs on total CO_2-eq emissions and supporting the reliability of the hotspot identification.

The results of the one-at-a-time sensitivity analysis are presented in the tornado chart shown in Figure 3, illustrating the relative influence of variations in key inventory parameters on total annual $CO_{2\text{-eq}}$ emissions. Fuel consumption, including natural gas, diesel, and gasoline, was varied by ±20% and exhibited the highest sensitivity among all evaluated parameters. In particular, changes in natural gas consumption in the kiln system led to the largest deviation from the baseline emissions, resulting in variations of approximately -13.32% to +13.32% in total $CO_{2\text{-eq}}$ emissions. This outcome reflects the dominant contribution of fuel use to the overall carbon footprint of the ceramic tile production system.

Electricity consumption was also varied by ±20% and emerged as the second most influential parameter in the sensitivity analysis. Variations in electricity input resulted in changes of approximately -6.12% to +6.12% relative to the baseline emissions.

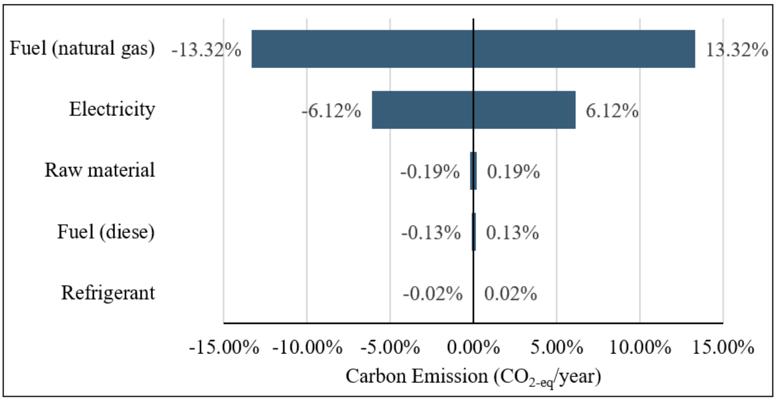

Figure 3. Tornado chart illustrating one-at-a-time sensitivity analysis of total annual carbon emissions from ceramic tile production, showing the relative influence of key input parameters. Positive and negative bars represent ± variation of each parameter around the baseline scenario

Although less pronounced than the effect of fuel consumption, the results indicate that electricity use remains a significant contributor to the variability of total emissions due to its involvement across multiple production stages.

In contrast, raw material inputs were varied by ±10% and produced only minor changes in total $CO_{2\text{-eq}}$ emissions, with deviations remaining below ±0.2% from the baseline. Similarly, refrigerant use, also varied by ±10%, resulted in negligible changes in total emissions. These findings indicate that total carbon emissions from ceramic tile production are primarily sensitive to energy-related parameters, while non-energy inputs exhibit limited influence within the tested variation ranges.

The sensitivity analysis provides important insights into the structural drivers of carbon emissions in ceramic tile production and confirms the robustness of the hotspot identification derived from the baseline LCA results. For fuel inputs (natural gas and diesel), a ±20% variation range was selected, as LCA literature on industrial systems commonly indicates that such a range conservatively represents operational variability and data uncertainty at the plant level. For example, a previous study conducted a sensitivity analysis by increasing and decreasing natural gas consumption by 20%, resulting in an approximately 7% change in global warming potential (GWP) (Hubbard et al. 2020). This finding suggests that a ±20% variation in fuel inputs leads to proportional environmental changes and can therefore be considered a reasonable range for testing model sensitivity. Although fewer studies explicitly address diesel consumption, its role as a major fossil energy carrier justifies the application of a similar ±20% range to account for fluctuations in consumption and uncertainty in diesel-related emission data.

The pronounced sensitivity of total $CO_{2\text{-eq}}$ emissions to variations in fuel consumption, particularly natural gas used in kiln firing, reflects the fundamentally energy-intensive nature of ceramic manufacturing. High-temperature firing processes operate continuously and dominate thermal energy demand; consequently, even conservative variations in fuel input (±20%) lead to substantial shifts in total emissions (approximately -13.32% to +13.32%). This finding is consistent with previous LCA studies on ceramic and other high-temperature industries, which consistently identify kiln systems as the primary leverage point for emission mitigation. Importantly, the magnitude of this sensitivity suggests that uncertainties in fuel consumption data, such as daily production fluctuations, burner efficiency variations, or measurement limitations, can significantly influence absolute emission estimates, while still preserving the relative ranking of emission sources.

A ±20% variation range was also applied to electricity consumption, consistent with practices commonly reported in LCA studies. Previous study, for instance, applied a ±20% variation to electricity input, which resulted in an approximately ±3.8% change in GWP (Hubbard et al. 2020). This indicates that electricity demand at the plant level may realistically vary by up to 20%, due to factors such as process load fluctuations or variations in grid supply conditions, while remaining within plausible operational scenarios.

This range also captures uncertainty associated with electrical energy intensity, including equipment efficiency and utilisation factors, without overstating variability beyond realistic industrial conditions.

For raw materials such as calcite, dolomite, and other fillers, LCA literature rarely provides explicit variation ranges. Raw material composition is generally governed by process formulations and tends to remain relatively stable across production cycles. Consequently, a narrower range of ±10-20% was assumed to conservatively capture potential variability arising from differences in material supply, quality, or inventory data uncertainty. This range also accounts for uncertainties related to material properties, such as chemical composition or moisture content, without exaggerating variability. While some LCA studies in other contexts, such as waste management, have explored much broader composition ranges, a more moderate assumption was adopted here in line with standard industrial LCA practice.

For refrigerants (e.g., R410A and R407C), a ±10% variation range was applied, reflecting their relatively small contribution to total LCA results despite their high global warming potential. As an illustration, previous research reported that leakage of R410A contributed approximately 3% of total GWP in air conditioning systems (Ross & Cheah, 2017). Given the relatively small absolute magnitude of refrigerant-related emissions, a narrower variation range was considered appropriate to represent uncertainty in refrigerant charging and leakage rates at the plant scale. A ±10% range was therefore deemed sufficiently conservative to reflect realistic uncertainty in refrigerant use while ensuring that such variations do not disproportionately influence the overall LCA outcomes.

In contrast, the limited sensitivity of total emissions to variations in raw material inputs and refrigerant use demonstrates that non-energy parameters play a comparatively minor role in shaping the overall LCA outcome within the tested uncertainty ranges. Variations of ±10% in raw material consumption resulted in deviations of less than ±0.2%, reflecting both the relatively small contribution of material-related emissions and the stability of ceramic body formulations in industrial practice. Similarly, refrigerant-related emissions, despite their high global warming potentials, exhibited negligible influence on total results due to their small absolute quantities. These findings indicate that uncertainties associated with material composition, supply variability, or refrigerant leakage rates are unlikely to alter the central conclusions of this study, thereby reinforcing the robustness of the identified energy-related emission hotspots.

From an industrial and policy perspective, the sensitivity results provide clear guidance for prioritising emission reduction strategies in ceramic manufacturing. Measures targeting kiln fuel efficiency, such as waste heat recovery, improved insulation, burner optimisation, and partial substitution with lower-carbon fuels, are likely to deliver the largest and most reliable emission reductions. Electricity-related measures, including process optimisation and procurement of lower-carbon electricity, represent secondary but still meaningful opportunities. Conversely, efforts focused primarily on modifying raw material inputs or refrigerant management, while relevant for comprehensive environmental management, are unlikely to yield substantial reductions in overall carbon emissions. Integrating these sensitivity insights with life-cycle cost considerations will be critical to translating environmental priorities into economically viable decarbonization strategies for the ceramic industry.

Emission Reduction

Emission reduction scenarios were developed based on the emission distribution identified in the baseline assessment, with particular emphasis on fuel combustion and electricity use as the principal emission sources. The scenarios were derived directly from the dominant contributors identified in Figure 2, ensuring that the proposed mitigation measures target empirically observed emission hotspots rather than hypothetical interventions. A linear modelling approach was applied, assuming that percentage reductions in energy consumption would result in proportional reductions in $CO_{2\text{-eq}}$ emissions. The analysis further assumed constant production output, minimal additional operational costs, and no changes in fuel prices or electricity tariffs, allowing the scenarios to reflect technically realistic improvements under current operating conditions.

Waste heat recovery (WHR) was evaluated as a primary mitigation option, based on the premise that a portion of thermal energy contained in kiln exhaust gases could be recovered for preheating incoming air or raw materials. This option was selected due to its compatibility with existing kiln configurations commonly used in ceramic manufacturing. A conservative 15% reduction in fuel-related emissions was assumed to account for

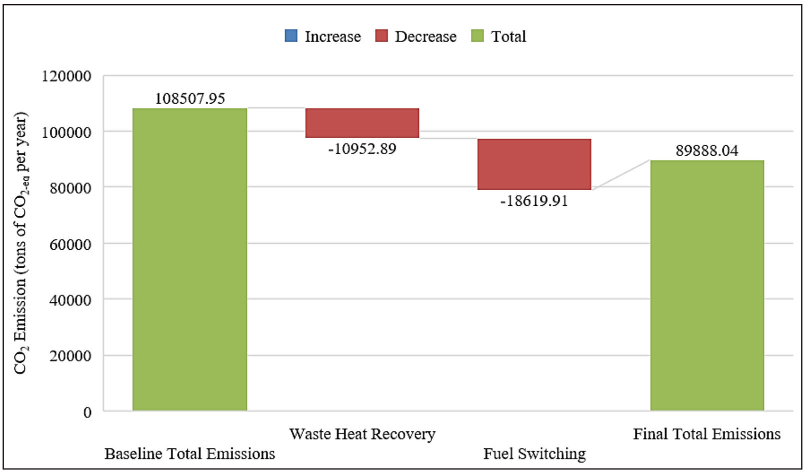

Figure 4. Stepwise emission reduction pathway for ceramic tile production under waste heat recovery (WHR) and combined fuel switching scenarios

variations in kiln design and flue gas temperature. Based on this assumption, emissions were reduced by 10,952.888 tons of $CO_{2\text{-eq}}$ per year, resulting in a revised total emission level of 97,555.062 tons of $CO_{2\text{-eq}}$ per year.

The second scenario integrates Waste Heat Recovery (WHR) with partial substitution of natural gas by biogas and hydrogen-enriched fuel, representing a progressive decarbonization pathway rather than full fuel replacement. In this scenario, an additional 30% reduction was applied specifically to the remaining fuel-related emissions after WHR implementation, consistent with values reported in the literature. As a result, total annual emissions decreased to 89,888.04 tons of $CO_{2\text{-eq}}$ per year, corresponding to an overall reduction of approximately 17.17% relative to the baseline emissions shown in Figure 4.

The emission reduction estimates are based on the technical assumptions summarised in Table 5, ensuring consistency between model inputs and reported results. The emission reduction scenarios evaluated in this study demonstrate that targeted interventions focusing on thermal efficiency and fuel composition can yield meaningful emission reductions in ceramic tile manufacturing. Waste heat recovery represents a particularly attractive option, as ceramic kilns typically lose 20-30% of thermal energy through exhaust gases. By explicitly linking mitigation options to the dominant emission sources identified in the baseline assessment, the analysis provides a coherent pathway from hotspot identification to intervention selection. Previous studies have similarly identified kiln systems as the most effective targets for emission mitigation, reinforcing the relevance of the selected approach (Desole et al. 2024; Quinteiro et al. 2022).

The practical feasibility of these mitigation options is supported by the existing kiln configuration at the studied facility, which relies on natural gas-fired thermal processes and therefore offers clear opportunities for heat recovery and fuel optimisation. Waste heat recovery can be integrated into the current system with relatively limited process disruption, particularly by utilising exhaust heat for preheating incoming air or materials. However, its implementation may require careful engineering design, space availability, and maintenance planning to ensure stable performance under continuous production conditions. In contrast, partial fuel substitution with biogas and hydrogen-enriched fuel may face greater operational constraints, including burner compatibility, fuel supply reliability, and the need for retrofitting of combustion systems. For a facility of this scale, such measures are more realistically implemented in a phased manner, allowing technical adjustments and operational learning to occur gradually while maintaining production continuity. Therefore, the estimated emission reductions represent technically feasible pathways, although their actual deployment would depend on plant-specific engineering and infrastructure readiness.

Reported reductions in energy consumption associated with WHR range from 8% to 25%, depending on kiln design and operating conditions (Yin et al. 2017). The 15%

reduction assumed in this study, therefore, falls within a conservative and technically realistic range, particularly for facilities operating conventional natural gas-fired kilns without integrated heat recovery. Beyond technological interventions, organisational measures such as energy management systems and ISO 50001 certification have been shown to play a critical role in sustaining efficiency gains through continuous monitoring, operator training, and maintenance optimisation (Prasetya et al. 2021), highlighting that operational practices can be as influential as equipment upgrades.

Combining WHR with partial fuel substitution further enhances emission reduction potential. Previous LCA-based models suggest that replacing natural gas with biogas or hydrogen-enriched fuel can reduce CO_2 emissions by approximately 30-50% in ceramic tile production systems (Saavedra & Osma, 2025). Framing fuel switching as a partial and gradual substitution, rather than a complete replacement, reflects realistic constraints related to fuel availability, burner compatibility, and cost. Additional measures, such as solar-assisted preheating, have also been proposed as complementary strategies, particularly in regions with high solar availability (Kumar et al. 2022), offering opportunities to reduce fossil fuel demand without disrupting core thermal processes.

Importantly, the mitigation pathways evaluated in this study do not rely on assumptions of immediate or complete energy system decarbonisation. Instead, they reflect incremental and technically feasible strategies that can be implemented within existing industrial infrastructure and current energy system constraints. While plant-level interventions can deliver significant near-term emission reductions, deeper decarbonisation will ultimately depend on broader transitions in national electricity generation toward cleaner energy sources. In this sense, the scenarios provide a pragmatic bridge between current operational realities and longer-term sustainability objectives.

Table 8

Comparison of emission reduction and life cycle cost results for WHR-only and combined mitigation scenarios

Parameter	**Scenario 1: WHR nly**	**Scenario 2: WHR + Fuel Substitution**
Baseline emission (t CO_2/y)	108,507.95	108,507.95
Emission after mitigation (t CO_2/y)	97,555.06	89,888.04
CO_2 avoided (t CO_2/y)	10,952.89	18,619.91
Emission reduction (%)	10.09%	17.16%
CAPEX (USD)	1,200,000.00	1800000
Annual net cost (USD/y)	1,724,285.89	781,291
Total CO_2 avoided (t CO_2)	164,293	279,299
NPV of total cost (USD)	-13,558,988.35	-4887440.301
Cost per ton CO_2 avoided (USD/t)	-82.53	-17.50

The results suggest that integrating life cycle assessment with incremental improvement scenarios offers a useful framework for guiding emission reduction strategies in ceramic industries, particularly in regions where rapid energy system decarbonisation remains challenging.

Life Cycle Cost

The life cycle cost (LCC) results of the evaluated mitigation scenarios are presented in Table 8, which compares the environmental and economic performance of the WHR-only scenario and the combined WHR with fuel substitution scenario. Under Scenario 1, the application of waste heat recovery reduced annual CO_2 emissions from 108,507.95 t CO_2/y to 97,555.06 t CO_2/y, corresponding to an avoided emission of 10,952.89 t CO_2/y or a reduction of 10.09%. Over the assumed technical lifetime of 15 years, the cumulative avoided emissions reached approximately 164,293 t CO_2.

From an economic standpoint, Scenario 1 required a capital investment of USD 1.2 million. Nevertheless, the significant reduction in natural gas consumption generated substantial operational savings, resulting in an annual net cost benefit of USD 1.72 million. When discounted using an 8% discount rate, the net present value (NPV) of the total cost over the system lifetime was estimated at -13.56 million USD. Consequently, the cost per ton of CO_2 avoided reached -82.53 USD/t CO_2, indicating that the WHR system provides both emission mitigation and strong economic returns.

In Scenario 2, which integrates WHR with partial substitution of natural gas by biogas and hydrogen-enriched fuel, annual emissions were further reduced to 89,888.04 t CO_2/y. This corresponds to an avoided emission of 18,619.91 t CO_2/y or a total reduction of 17.16% relative to the baseline. Over the 15-year operational period, the cumulative avoided emissions increased significantly to approximately 279,299 t CO_2.

The combined scenario required a higher capital expenditure of USD 1.8 million due to additional fuel system retrofitting. Although operational fuel costs increased, the scenario still produced a negative NPV of -4.89 million USD. The resulting cost per ton of CO_2 avoided was -17.50 USD/t CO_2, confirming that the combined mitigation pathway remains economically feasible while achieving deeper emission reductions.

The LCC results indicate that waste heat recovery (WHR) represents a highly cost-effective mitigation option for the ceramic industry. The WHR-only scenario yields a strongly negative abatement cost, indicating that the fuel cost savings generated during operation are sufficient to offset both the initial investment and annual operating expenses. This finding is consistent with empirical studies in cement and other high-temperature industrial sectors, which report that WHR systems can simultaneously reduce production costs and greenhouse gas emissions, particularly when bottoming-cycle technologies such as Organic Rankine Cycles (ORC) or heat utilisation for air and raw material preheating are integrated into kiln systems (Marenco-Porto et al. 2023).

In contrast, the combined scenario integrating WHR with partial fuel substitution using biogas and hydrogen-enriched fuel achieves a substantially higher absolute emission reduction but exhibits a lower marginal cost efficiency. This outcome is primarily associated with the price premium of low-carbon fuels and the additional capital and retrofit requirements needed to enable fuel switching. Similar trends have been reported in previous decarbonization pathway analyses for energy-intensive industries, which emphasise that energy efficiency measures (such as WHR) generally represent no-regret options, while fuel substitution pathways often face significant economic and infrastructural barriers unless supported by carbon pricing mechanisms, targeted subsidies, or long-term policy frameworks (Lechtenböhmer et al. 2016).

From a strategic perspective, these results support a hierarchical decarbonization approach. Thermal efficiency improvements, including WHR implementation, should be prioritised as short- to medium-term measures capable of delivering immediate emission reductions together with direct economic benefits. Fuel substitution strategies, such as the gradual introduction of biogas and hydrogen blends, are more suitable as medium- to long-term options, particularly as fuel supply chains mature and supportive policy instruments become available. In this context, the integrated LCA & LCC framework applied in this study provides a robust decision-support tool, enabling industrial stakeholders and policymakers to quantitatively assess trade-offs between emission reduction depth and economic feasibility in the ceramic manufacturing sector.

CONCLUSION

This study applied a gate-to-gate life cycle assessment to a large-scale ceramic tile manufacturing facility in Indonesia, PT Sinar Karya Duta Abadi, revealing a total carbon footprint of 108,507.95 t $CO_{2\text{-eq}}$ per year, equivalent to 7.3401 kg $CO_{2\text{-eq}}/m^2$ of ceramic tiles. Fuel combustion in kiln operations and electricity consumption were identified as the dominant emission hotspots, jointly contributing approximately 97% of total emissions, a finding further confirmed by sensitivity analysis showing strong responsiveness of overall emissions to variations in energy-related parameters. Based on these results, emission reduction scenarios were developed, indicating that waste heat recovery alone could reduce emissions by 10.09%, while its integration with partial fuel substitution decreased total emissions by up to 17.16%. Life cycle cost analysis demonstrated that both mitigation pathways are economically feasible, with negative abatement costs of -82.53 USD/t CO_2 for the WHR scenario and -17.50 USD/t CO_2 for the combined scenario, highlighting that meaningful emission reductions can be achieved alongside long-term economic benefits.

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