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Article

Benchmarking the Environmental Performance of Clinker Production: A Life Cycle Assessment Based on Real Industrial Data

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Abstract

The cement industry is one of the largest industrial sources of anthropogenic carbon dioxide (CO₂) emissions, with clinker production representing the most energy- and carbon-intensive stage of cement manufacturing. Life cycle assessment (LCA) is widely used to quantify the environmental impacts of clinker production and to support benchmarking of energy use and greenhouse gas emissions. However, plant-level benchmarking studies based on real industrial operational data remain limited, and the relationship between energy efficiency improvements and overall climate change impacts is not always clearly resolved. In this study, the environmental performance of clinker production at a representative integrated cement plant is assessed using a cradle-to-gate LCA approach. The analysis is based on real industrial operational data and uses a functional unit of 1 t of Portland cement clinker. Life cycle inventory data are compiled for raw material inputs, energy consumption, and direct CO₂ emissions, and the results are benchmarked against a harmonized literature-based reference dataset. Global warming potential (GWP) is evaluated using IPCC 100-year characterization factors. The results show that the case-study plant exhibits lower thermal energy demand (3162 MJ/t clinker) and electricity consumption (52.23 kWh/t clinker) compared to the literature benchmark. Despite these improvements in energy-related indicators, the total GWP of clinker production at the case-study plant (1010 kg CO₂-eq/t clinker) is comparable to the benchmark value (995 kg CO₂-eq/t clinker). Contribution analysis indicates that process-related CO₂ emissions from limestone calcination dominate the total GWP, accounting for approximately 73% of total emissions. These findings demonstrate that improvements in energy efficiency alone do not necessarily translate into proportional reductions in overall climate change impacts for clinker production. The study highlights the importance of harmonized benchmarking and underscores the need for mitigation strategies that directly address process-related emissions in order to achieve substantial reductions in greenhouse gas emissions in the cement industry.

Keywords: clinker production; cement industry; life cycle assessment; life cycle inventory; benchmarking; global warming potential; carbon dioxide emissions

1. Introduction

The cement industry plays a critical role in supporting global infrastructure development, yet it is also one of the most energy- and carbon-intensive industrial sectors worldwide [1–3]. Cement production is responsible for approximately 7–8% of global anthropogenic carbon dioxide (CO₂) emissions, with the majority originating from clinker production, the intermediate product formed during high-temperature processing of limestone-based raw materials [4–10]. Clinker production requires substantial thermal energy input and involves the chemical decomposition of calcium carbonate, making it inherently carbon intensive. As global demand for cement continues to grow, reducing the environmental impact of clinker production has become a central challenge for both industry and policy makers [11].

Life cycle assessment (LCA) has been widely applied as a systematic framework for quantifying the environmental impacts associated with cement and clinker production across different system boundaries and geographical contexts [12–14]. Numerous LCA studies have consistently demonstrated that greenhouse gas emissions from clinker production are dominated by two main sources: process-related emissions from limestone calcination and energy-related emissions from fuel combustion in the kiln system [15]. Process-related emissions arise directly from the clinker formation chemistry and typically account for the largest share of total emissions, while fuel-related emissions are linked to kiln operation and energy efficiency [16]. Although improvements in energy efficiency, alternative fuels, and waste heat recovery have contributed to reducing fuel-related emissions, the intrinsic nature of calcination-related CO₂ emissions limits the overall mitigation potential achievable through energy measures alone [17].

To support performance evaluation and emission reduction strategies, benchmarking of clinker production systems using life cycle indicators has gained increasing attention in the literature. Benchmarking enables the comparison of key performance indicators, such as thermal energy intensity, electricity consumption, and greenhouse gas emissions, across different plants and technologies [18]. Such comparisons provide valuable insights into relative performance levels, identify potential efficiency gaps, and support the dissemination of best practices within the cement industry [19]. However, the interpretation of benchmarking results strongly depends on the consistency of methodological choices, including the functional unit, system boundary, and life cycle impact assessment approach [20].

Despite the growing availability of life cycle inventory data for clinker production, many existing benchmark datasets are derived from generic or aggregated literature values. These datasets may not fully capture the operational characteristics of modern integrated cement plants operating under real industrial conditions [21]. Plant-level benchmarking studies based on real industrial operational datasets remain relatively limited, particularly those that explicitly harmonize foreground plant data with literature-based reference inventories. The lack of transparent and methodologically consistent comparisons constrains the interpretation of benchmarking results and may obscure the relationship between improvements in energy efficiency and overall climate change impacts.

The objective of this study is to assess the environmental performance of clinker production at a representative integrated cement plant using real industrial operational data and to benchmark the results against a literature-based reference dataset. A cradle-to-gate life cycle assessment is conducted with a functional unit of 1 t of Portland cement clinker, focusing on global warming potential (GWP) using IPCC 100-year characterization factors. By harmonizing methodological choices, inventory assumptions, and background data, this study aims to provide a transparent and robust comparison of energy use and greenhouse gas emissions. In particular, the analysis seeks to clarify the extent to which improvements in energy-related performance indicators translate into reductions in total climate change impacts. The findings contribute to the scientific discussion on clinker production benchmarking and support the development of more effective emission mitigation strategies in the cement industry.

2. Materials and Methods

2.1. Case Study Description

This study investigates a representative integrated cement manufacturing plant using real industrial operational data compiled in the DiB cement plant dataset. To preserve confidentiality, the identity and exact location of the plant are anonymized. The facility operates a conventional clinker-based cement production line and is considered representative of modern cement plants employing rotary kiln technology with preheating and precalcination stages.

2.2. Goal and Scope Definition

Figure 1 illustrates a simplified overview of the cement production process considered in this study. Raw materials, primarily limestone and corrective additives, are proportioned and ground to

produce raw meal. The raw meal is subsequently preheated and partially calcined before entering the rotary kiln, where clinker formation occurs at high temperature. After clinker cooling, the material is transported to the finish grinding stage, where it is ground and blended with gypsum to produce cement.

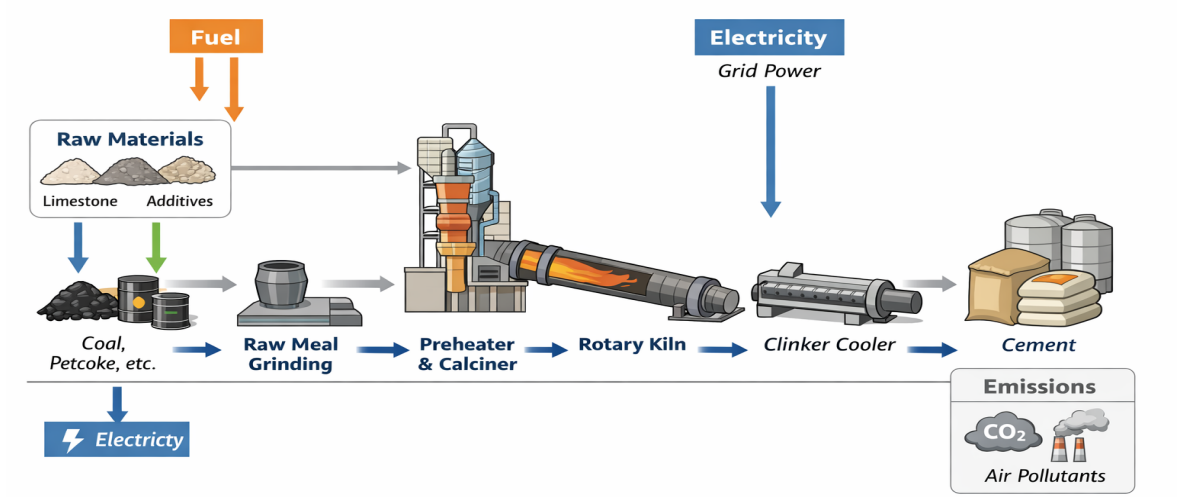


Figure 1. Simplified process overview of the case-study cement plant, indicating major unit operations and main energy and emission flows.

Thermal energy required for clinker production is supplied mainly by fossil fuel-based energy sources, while electricity from the national grid is consumed across major unit operations, including raw meal grinding, kiln auxiliaries, clinker cooling, and cement grinding. Direct emissions, primarily carbon dioxide originating from both fuel combustion and limestone calcination, are released during the clinker production stage.

The main technical and operational characteristics of the case-study plant are summarized in Table 1. These characteristics provide the contextual basis for the life cycle assessment and enable a transparent benchmarking of the environmental performance of the case-study plant against literature-based reference data.

Table 1. Main characteristics of the case-study cement plant.

Parameter	Value
Plant type	Integrated cement plant
Geographical scope	Representative plant (anonymized)
Main product	Portland cement clinker
Functional unit	1 t clinker
Kiln technology	Rotary kiln with preheater and precalciner
Primary thermal energy source	Fossil fuel-based (mixed fuel system)
Electricity supply	National grid electricity
Clinker-to-cement ratio	> 0.70 (typical OPC range)
Data representativeness	Multi-year operational average
Data source	DiB cement plant dataset

The goal of this study is to assess the environmental performance of clinker production at a representative integrated cement plant and to benchmark the results against literature-based reference data. The assessment is intended to support scientific discussion and industrial benchmarking by

identifying key contributors to environmental impacts and potential improvement opportunities within the clinker production process.

The methodological choices adopted in the life cycle assessment, including the definition of the functional unit, system boundary, impact assessment method, and data sources, are summarized in Table 2.

The functional unit (FU) is defined as 1 tonne of Portland cement clinker produced at the plant gate. Clinker is selected as the functional unit because it represents the most energy- and carbon-intensive stage of cement manufacturing and is commonly used as a reference unit in life cycle assessment studies, allowing for consistent comparison with published literature.

A cradle-to-gate system boundary is adopted. The system includes all processes from raw material extraction and preparation through clinker production and cooling, while downstream processes such as cement blending, packaging, distribution, use, and end-of-life are excluded. The system boundary applied in this study is illustrated in Figure 2.

Table 2. Goal, scope, and methodological choices of the life cycle assessment.

Item	Description
Goal of the study	Environmental performance evaluation and benchmarking of clinker production
Intended application	Scientific analysis and industrial benchmarking
Functional unit	1 t of Portland cement clinker
System boundary	Cradle-to-gate
Included processes	Raw material extraction and preparation; raw meal grinding; preheating and calcination; clinker production in the rotary kiln; clinker cooling
Excluded processes	Cement blending, packaging, distribution, use, and end-of-life
Life cycle impact assessment method	IPCC 100-year GWP (midpoint level)
Allocation procedure	No allocation required (single main product)
Cut-off criteria	Flows contributing less than 1% of mass, energy, or environmental impact
Temporal representativeness	Multi-year average operational data
Geographical representativeness	Representative integrated cement plant (anonymized)
Technological representativeness	Modern rotary kiln with preheater and precalciner
LCA software	openLCA
Primary data source	DiB cement plant dataset
Benchmark data source	Rhaouti et al. (2024)

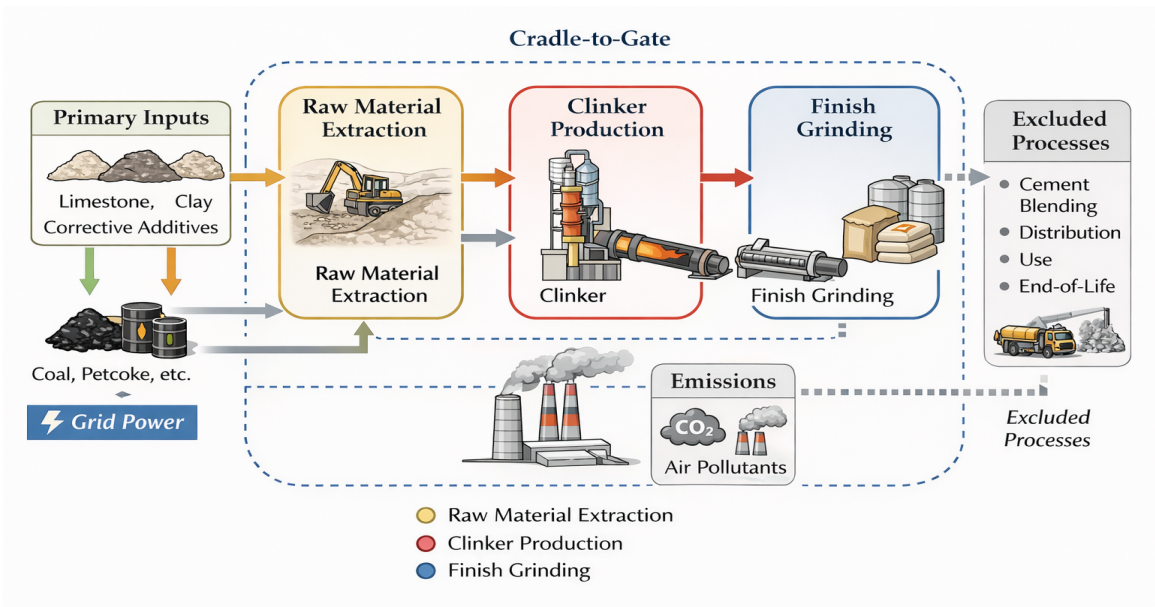


Figure 2. Simplified process overview of the case-study cement plant, indicating major unit operations and main energy and emission flows.

Life cycle impact assessment (LCIA) is performed at the midpoint level with a primary focus on climate change impacts. Global warming potential (GWP) is calculated using IPCC 100-year

characterization factors. This indicator is selected due to its relevance for evaluating greenhouse gas emissions associated with clinker production.

Clinker production is treated as a single main product within the defined system boundary; therefore, no allocation procedures are required. Cut-off criteria are applied such that material and energy flows contributing less than 1% to the total mass, energy use, or environmental impact are excluded, while ensuring that at least 99% of the total environmental burden is captured.

Foreground inventory data are derived from real industrial operational records compiled in the DiB cement plant dataset and represent a multi-year average of plant operation. The geographical and technological scope corresponds to a modern integrated cement plant equipped with a rotary kiln, preheater, and precalciner. Life cycle modeling and impact assessment are conducted using the *openLCA* software environment.

2.3. Life Cycle Inventory

The life cycle inventory (LCI) was established using foreground industrial data and a literature-based benchmark dataset. Foreground data for the case-study plant were obtained from the DiB cement plant dataset and correspond to the production of 1 t of clinker. The inventory includes raw material inputs, fuel consumption, electricity use, and direct CO₂ emissions associated with clinker production.

Table 3 reports the foreground inventory for the case-study plant. Raw material inputs comprise limestone and corrective materials (e.g., flue dust, red mud, laterite, and crushed slag). Electricity consumption is reported as the sum of the main unit operations listed in the DiB dataset (limestone crushing, raw meal preparation, coal milling, and kiln operation). Thermal energy demand is calculated from the reported fuel mix by converting the fuel masses to energy using their lower heating values (LHVs) provided in the DiB dataset.

Table 3. Life cycle inventory of clinker production based on the DiB cement plant dataset reported by Basavaraj [22] (per functional unit of 1 t clinker).

Inventory flow	Amount	Unit
<i>Raw material inputs</i>		
Limestone	1420.00	kg
Corrective materials (flue dust + red mud + laterite + crushed slag)	125.00	kg
<i>Energy inputs</i>		
Thermal energy (kiln fuels) ^a	3162.44	MJ
Electricity consumption (total) ^b	52.23	kWh
<i>Direct emissions</i>		
CO ₂ from calcination ^c	738.40	kg
CO ₂ from fuel combustion ^d	271.63	kg
Total direct CO ₂ emissions	1010.03	kg

^aCalculated as $\sum(m_i \times LHV_i)$ using fuel masses (coal 32 kg, pet coke 60 kg, pharmaceutical solid waste 3 kg, carbon black 3 kg, pharmaceutical liquid waste 2 kg) and calorific contents reported in the DiB dataset.

^bSum of electricity uses for limestone crushing, raw meal preparation, coal milling, and kiln operation (DiB dataset).

^cEstimated from limestone input using the DiB calcination factor (0.520 kg CO₂/kg limestone).

^dCalculated as $\sum(m_i \times EF_i)$ using DiB fuel emission factors (kg CO₂/kg fuel).

Direct CO₂ emissions are reported as the sum of (i) process-related CO₂ from calcination and (ii) fuel-combustion CO₂. Process CO₂ is estimated from limestone input using the CO₂ characterization factor for limestone reported in the DiB dataset (kg CO₂/kg limestone). Fuel-combustion CO₂ is calculated from the reported fuel masses using fuel-specific emission factors (kg CO₂/kg fuel) reported in the same dataset. The resulting total direct CO₂ emissions are provided in Table 3.

For benchmarking, a literature-based clinker inventory was compiled from Rhaouti et al. (2024). The reference inventory is reported per 1 kg of clinker in the original dataset; therefore, all flows were

scaled to the functional unit of 1 t of clinker to ensure comparability. Table 4 summarizes the key benchmark parameters (materials, electricity, fuel input, and total direct fossil CO₂ emissions). For consistent comparison of energy intensity when only fuel mass is reported, an energy-equivalent value can be derived by applying the same LHV assumption used for the case-study fuels.

Background processes (e.g., upstream electricity generation and fuel supply) are modeled using secondary datasets within the *openLCA* software environment, and consistent background assumptions are applied across both the case-study and literature-based inventories to avoid systematic bias in the benchmarking results.

Table 4. Literature-based life cycle inventory for clinker production used for benchmarking (adapted from the dataset reported by Rhaouti et al. [23]; per 1 t clinker).

Inventory flow	Amount	Unit
<i>Raw material inputs</i>		
Limestone, processed	1410.00	kg
Corrective materials (shale + bauxite + iron ore)	106.53	kg
<i>Energy inputs</i>		
Petroleum coke	98.00	kg
Thermal energy (derived from petcoke) ^e	3364.34	MJ
Electricity consumption (medium voltage)	74.00	kWh
<i>Direct emissions</i>		
Carbon dioxide, fossil (total)	995.00	kg

^eThermal energy derived using the same petcoke LHV as used for Table 3 (34.33 MJ/kg) to allow consistent energy-intensity benchmarking when only fuel mass is reported.

2.4. Benchmarking Approach

The benchmarking analysis is conducted by comparing the life cycle inventory and impact assessment results of the case-study plant with the literature-based reference dataset derived from Rhaouti et al. (2024). To ensure a consistent comparison, both inventories are harmonized to the same functional unit (1 t of clinker) and system boundary (cradle-to-gate), as defined in Section 2.2.

Key benchmarking indicators include thermal energy intensity (MJ/t clinker), electricity consumption (kWh/t clinker), and direct CO₂ emissions (kg CO₂/t clinker). Differences between the case-study plant and the benchmark values are quantified and discussed in relative terms to highlight deviations from literature-reported performance levels.

Where inventory parameters are reported at different levels of aggregation, harmonization is applied prior to comparison. In particular, when literature data report only aggregated fuel inputs or total CO₂ emissions, equivalent energy or emission values are derived using consistent assumptions with those applied to the foreground inventory. This approach ensures comparability while minimizing methodological bias.

The benchmarking results are interpreted to identify potential performance gaps and improvement opportunities in clinker production, with particular emphasis on energy efficiency and carbon intensity.

2.5. Uncertainty and Limitations

Several sources of uncertainty and limitation should be considered when interpreting the results of this study. First, the analysis is based on data from a single integrated cement plant. Although the plant is considered representative of modern clinker production technology, the results may not be fully generalizable to all cement plants, particularly those operating under different technological or regional conditions.

Second, while the foreground inventory data are derived from real industrial records and represent multi-year average operation, uncertainties remain due to measurement variability, data aggregation, and assumptions applied in the calculation of thermal energy demand and process-related CO₂

emissions. These uncertainties may influence the absolute values of the reported indicators but are not expected to alter the relative comparison between the case-study plant and the literature benchmark.

Third, the benchmarking analysis relies on literature-based inventory data that are reported at different levels of detail and aggregation. Despite harmonization efforts, residual differences in data quality, reporting conventions, and background assumptions may affect the comparability of results.

Finally, the assessment focuses on direct energy use and greenhouse gas emissions at the clinker production stage and does not account for downstream processes or broader environmental impact categories. Future work could address these limitations by including multiple plants, additional impact categories, and uncertainty analysis methods such as sensitivity or Monte Carlo analysis.

3. Results

3.1. Life Cycle Inventory Results

The life cycle inventory results for clinker production at the case-study plant and the literature-based benchmark are presented in Tables 3 and 4, respectively. The comparison focuses on material inputs, energy consumption, and direct carbon dioxide emissions, which constitute the main drivers of environmental impacts in clinker production. Regarding energy use, the case-study plant exhibits a thermal energy intensity of 3162 MJ/t clinker, compared to 3364 MJ/t clinker reported in the literature benchmark. This represents a reduction of approximately 6% in thermal energy demand, indicating a relatively efficient kiln operation at the case-study plant. The lower thermal energy intensity can be associated with differences in fuel mix composition, kiln operation efficiency, and heat recovery performance, although a detailed process-level assessment is beyond the scope of this inventory analysis.

Electricity consumption at the case-study plant amounts to 52.23 kWh/t clinker, which is substantially lower than the benchmark value of 74 kWh/t clinker. This corresponds to a reduction of about 29% and suggests improved electrical efficiency across major unit operations such as raw meal preparation, kiln auxiliaries, and clinker cooling. Lower electricity demand may reflect differences in equipment efficiency, process integration, and operational practices between the two systems. In terms of raw material inputs, the limestone requirement for clinker production at the case-study plant (1420 kg/t clinker) is comparable to the value reported in the literature benchmark (1410 kg/t clinker). This similarity indicates that both systems operate with comparable clinker chemistry and lime saturation levels. The case-study plant exhibits a slightly higher use of corrective materials, which can be attributed to differences in raw material quality and feed composition control strategies aimed at achieving the desired clinker mineralogy.

Direct carbon dioxide emissions at the case-study plant amount to 1010 kg CO₂/t clinker, including contributions from both calcination-related emissions and fuel combustion. This value is marginally higher than the benchmark emission level of 995 kg CO₂/t clinker reported in the literature. The difference is primarily driven by variations in fuel-related emissions and raw material carbonate content, which directly influence process CO₂ release during calcination. Overall, the inventory results indicate that the case-study plant performs favorably in terms of energy efficiency compared to the literature benchmark, particularly with respect to electricity consumption. At the same time, direct CO₂ emissions remain within the range reported in the literature, highlighting the dominant role of process-related emissions in clinker production. These inventory-level findings provide a robust basis for the life cycle impact assessment and benchmarking results discussed in the subsequent sections.

3.2. Global Warming Potential Results

The global warming potential (GWP) results for clinker production are presented in Figure 3 and are expressed per functional unit of 1 t of clinker. The results are derived from the life cycle inventory data reported in Tables 3 and 4 and represent the characterized climate change impacts associated with clinker production at the case-study plant and the literature-based reference system.

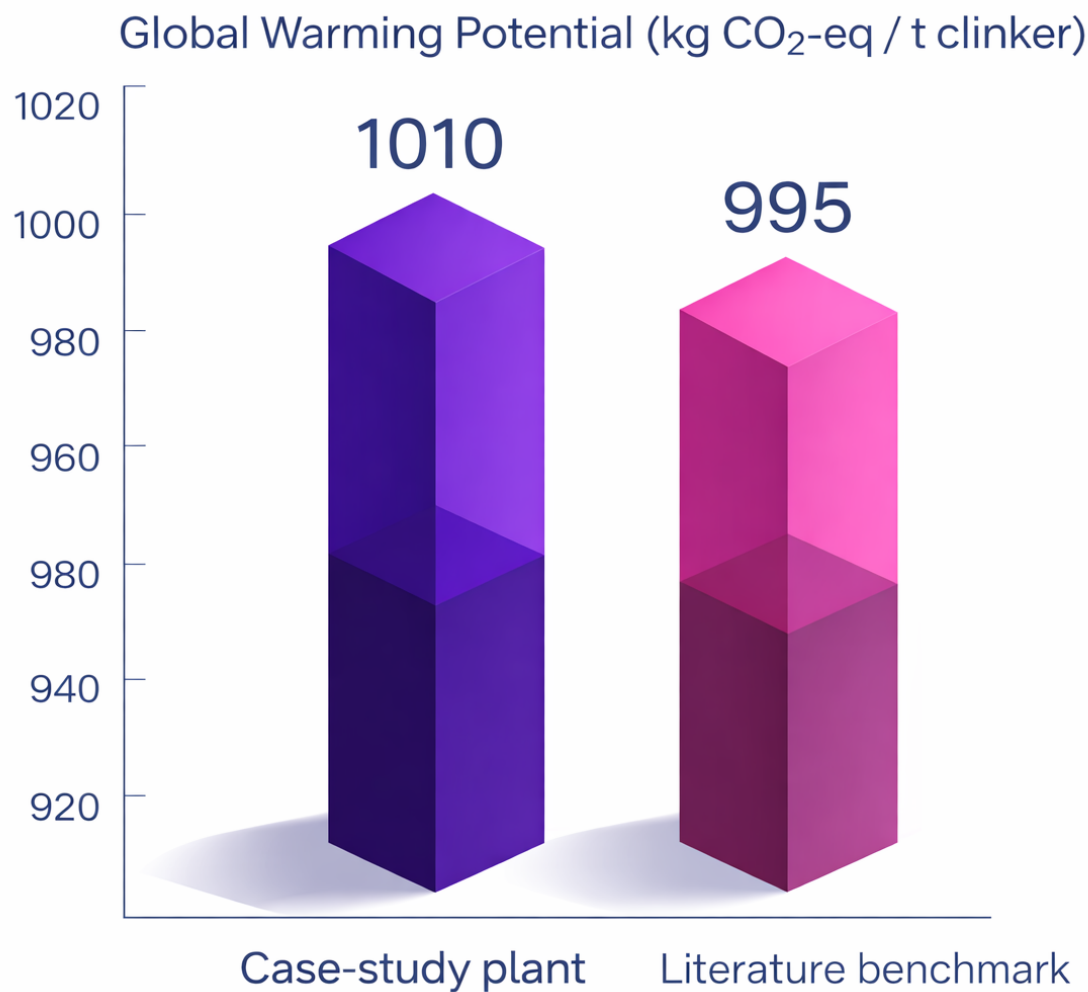


Figure 3. Comparison of the global warming potential (GWP) of clinker production at the case-study plant and the literature benchmark, expressed per functional unit of 1 t of clinker. The results highlight the relative difference in climate change impact between the two production systems.

The total GWP of the case-study plant is 1010 kg CO₂-eq/t clinker, while the literature-based benchmark reported by Rhaouti et al. (2024) amounts to 995 kg CO₂-eq/t clinker. The difference between the two systems is relatively small (approximately 1.5%), indicating that the overall climate change impact of the case-study plant is comparable to that reported for representative clinker production systems in the literature. This similarity suggests that the case-study plant operates within the typical performance range observed for modern integrated clinker production facilities.

Despite the lower thermal energy demand and electricity consumption observed for the case-study plant, the total GWP remains slightly higher than the benchmark value. This outcome reflects the dominant contribution of process-related CO₂ emissions from limestone calcination, which constitute the largest share of total greenhouse gas emissions in clinker production. As calcination-related emissions arise from the chemical decomposition of calcium carbonate, they are largely independent of improvements in thermal and electrical energy efficiency. Consequently, reductions in energy consumption primarily affect fuel-related emissions and result in only marginal changes in total GWP.

The GWP results therefore highlight the limited sensitivity of overall climate change impacts to energy efficiency improvements at the clinker production stage. Even when energy-related performance indicators show favorable values, the total GWP remains strongly governed by process-related emissions. Overall, the GWP results confirm that clinker production at the case-study plant operates within the typical emission range reported in the literature. These findings provide a consistent and

robust basis for the contribution analysis and benchmarking discussion presented in the subsequent sections.

3.3. Contribution Analysis

The contribution analysis examines the relative importance of different emission sources contributing to the total global warming potential (GWP) of clinker production at the case-study plant. The analysis focuses on process-related CO₂ emissions from limestone calcination and energy-related CO₂ emissions from fuel combustion. The results are illustrated in Figure 4.

Process-related CO₂ emissions from limestone calcination represent the dominant contribution to the total GWP, accounting for approximately 73% of total greenhouse gas emissions. This contribution is inherent to clinker production and results from the decomposition of calcium carbonate during the calcination process. As such, these emissions are largely independent of improvements in thermal or electrical energy efficiency. Fuel combustion contributes the remaining share of total GWP, accounting for approximately 27% of total emissions. Fuel-related emissions are directly associated with the thermal energy demand of the kiln system and the composition of the fuel mix used in clinker production.

Overall, the contribution analysis clearly indicates that process-related emissions from calcination are the primary driver of climate change impacts in clinker production, while fuel-related emissions constitute a secondary but still significant contribution. These results highlight the structural limitations of energy efficiency measures alone in achieving substantial reductions in total GWP and provide a basis for the benchmarking analysis presented in the next section.

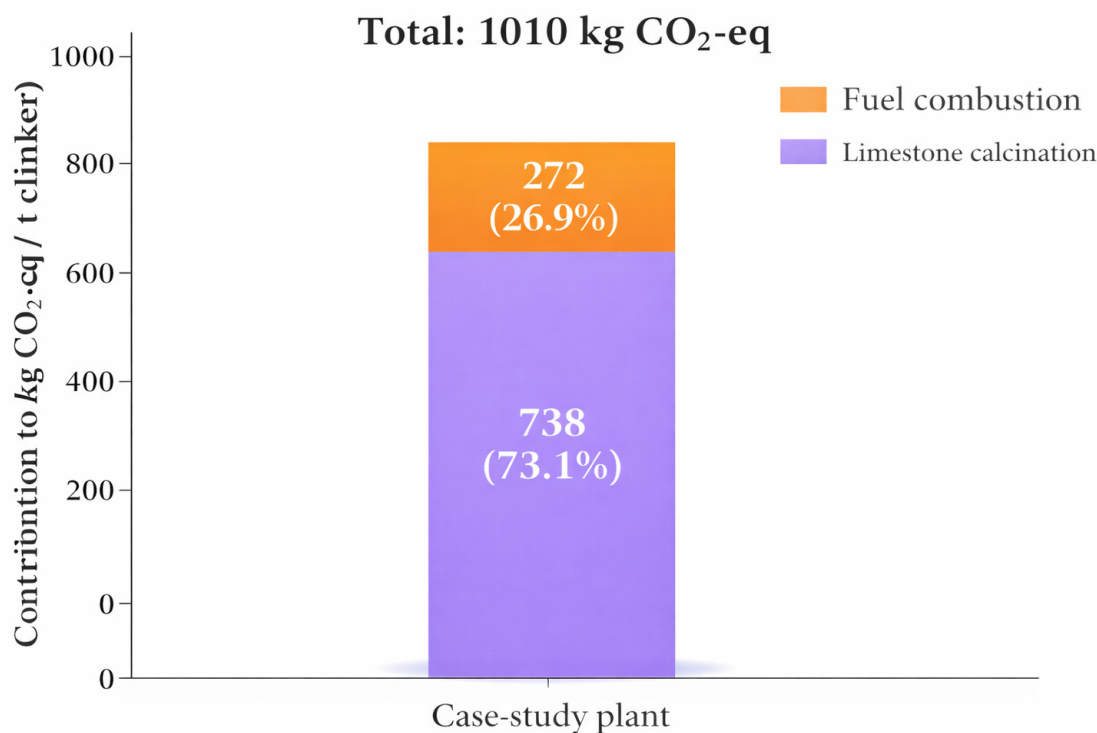


Figure 4. Contribution of process-related CO₂ emissions from calcination and energy-related emissions from fuel combustion to the total global warming potential of clinker production at the case-study plant.

3.4. Benchmarking Analysis

The benchmarking analysis evaluates the environmental performance of the case-study plant relative to a literature-based reference system reported by Rhaouti et al. (2024). The comparison is conducted using harmonized indicators expressed per functional unit of 1 t of clinker and focuses on thermal energy intensity, electricity consumption, and global warming potential (GWP).

As shown in Figure 5, the case-study plant demonstrates lower thermal energy demand (3162 MJ/t clinker) compared to the literature benchmark (3364 MJ/t clinker). Similarly, electricity consumption at the case-study plant (52.23 kWh/t clinker) is substantially lower than the benchmark value (74 kWh/t clinker). These results indicate a favorable energy efficiency performance of the case-study plant relative to the reference system. In contrast, the total GWP of the case-study plant (1010 kg CO₂-eq/t clinker) is comparable to that of the literature benchmark (995 kg CO₂-eq/t clinker), as illustrated in Figure 3. Despite improvements in energy-related indicators, the overall climate change impact remains similar between the two systems.

The benchmarking results confirm that reductions in energy consumption do not necessarily translate into proportional reductions in total GWP. This outcome is consistent with the contribution analysis presented in Section 3.3, which shows that process-related CO₂ emissions from limestone calcination dominate total emissions in both systems. Overall, the benchmarking analysis indicates that the case-study plant operates within the typical performance range reported for modern clinker production systems. The results provide a clear quantitative basis for interpreting the relative performance of the case-study plant and for contextualizing the findings within existing literature.

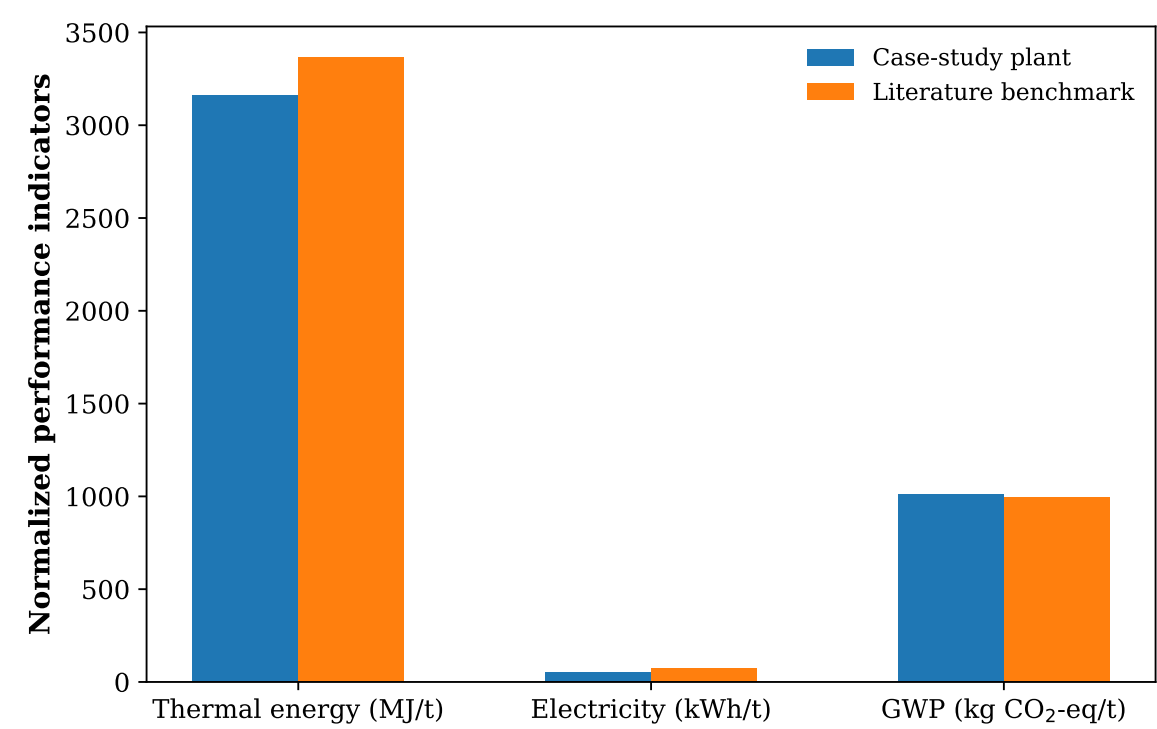


Figure 5. Benchmarking comparison of key performance indicators for clinker production at the case-study plant and the literature benchmark.

3.5. Summary of Key Results

This study assessed the life cycle inventory and global warming potential (GWP) of clinker production at a representative cement plant and benchmarked the results against literature-based reference data. The analysis was conducted using harmonized system boundaries and a consistent functional unit, enabling a transparent comparison of key performance indicators.

The life cycle inventory results indicated that the case-study plant performs favorably with respect to energy-related indicators. In particular, both thermal energy demand and electricity consumption were lower than the corresponding literature benchmark values. These findings suggest a relatively high level of operational energy efficiency at the case-study plant, reflecting differences in kiln operation, process integration, and electrical efficiency across major unit operations.

Despite the lower energy consumption, the total GWP of clinker production at the case-study plant was found to be comparable to that reported in the literature. The contribution analysis demonstrated that process-related CO₂ emissions from limestone calcination constitute the dominant share of total greenhouse gas emissions, whereas fuel combustion represents a secondary but still significant contributor. Electricity-related emissions account for a comparatively minor share of total GWP.

The benchmarking analysis further confirmed that improvements in energy efficiency do not necessarily result in proportional reductions in total climate change impacts. This outcome highlights the structural importance of process-related emissions in clinker production and explains the limited sensitivity of total GWP to variations in energy-related performance indicators.

Overall, the results show that the case-study plant operates within the typical performance range reported for modern clinker production systems. The findings provide a robust quantitative basis for the discussion of environmental performance, mitigation potential, and future improvement strategies presented in the following section.

4. Discussion

4.1. Interpretation of Energy Performance

The life cycle inventory results demonstrate that the case-study plant exhibits relatively favorable energy performance compared to the literature-based benchmark. Both thermal energy demand and electricity consumption are lower than the benchmark values reported by Rhaouti et al. (2024), indicating a comparatively efficient operation of the kiln system and auxiliary processes. Differences in energy performance among clinker production systems are widely documented in the literature and are commonly attributed to variations in kiln configuration, fuel mix, heat recovery efficiency, and operational practices.

The lower electricity consumption observed for the case-study plant suggests effective process integration and efficient operation of electrical equipment across major unit operations, such as raw meal preparation, kiln auxiliaries, and clinker cooling. While the present analysis does not investigate process-level operational details, the results are consistent with previous studies reporting that modern integrated plants can achieve substantial reductions in electrical energy demand through optimized process control and equipment efficiency.

4.2. Relationship Between Energy Efficiency and Global Warming Potential

Despite the observed advantages in energy-related indicators, the global warming potential of clinker production at the case-study plant remains comparable to the literature benchmark. This finding highlights the limited sensitivity of total climate change impact to improvements in energy efficiency alone. As demonstrated by the contribution analysis, process-related CO₂ emissions from limestone calcination dominate the total greenhouse gas emissions associated with clinker production [24–26].

Process-related emissions arise from the chemical decomposition of calcium carbonate during clinker formation and are therefore largely independent of thermal or electrical energy efficiency improvements [27]. Consequently, reductions in fuel-related emissions achieved through improved energy performance result in only modest changes in total GWP. This observation is consistent with previous life cycle assessment studies, which consistently identify calcination as the primary contributor to climate change impacts in clinker and cement production [28].

4.3. Benchmarking Implications for Clinker Production

From a benchmarking perspective, the results indicate that the case-study plant operates within the typical performance range reported for modern clinker production systems. The benchmarking analysis shows that superior energy efficiency does not necessarily translate into significantly lower total GWP, emphasizing the importance of interpreting benchmarking results in light of the relative contributions of different emission sources.

The comparison with literature data underscores the value of using harmonized functional units and system boundaries when benchmarking environmental performance. Without such harmonization, differences in reported results may reflect methodological inconsistencies rather than actual performance differences. The present study demonstrates that combining real industrial data with literature benchmarks provides a robust basis for contextualizing plant-level performance within the broader cement industry.

4.4. Implications for Emission Mitigation Strategies

The findings of this study have important implications for greenhouse gas mitigation strategies in the cement industry. While continued improvements in energy efficiency and fuel substitution remain essential for reducing fuel-related emissions, the dominance of process-related CO₂ emissions limits the overall mitigation potential of such measures. As a result, achieving substantial reductions in total greenhouse gas emissions will require strategies that directly address process-related emissions [29,30].

Potential mitigation options include clinker substitution through the use of supplementary cementitious materials, alternative raw materials with reduced carbonate content, and the implementation of carbon capture, utilization, and storage (CCUS) technologies [31–33]. The results presented here reinforce the need for an integrated mitigation approach that combines energy efficiency measures with process-oriented strategies to achieve meaningful reductions in the climate change impact of clinker production.

4.5. Limitations and Future Research

Several limitations of the present study should be acknowledged. First, the analysis is based on data from a single cement plant and therefore may not fully represent the variability of technologies, fuel mixes, and operating conditions across the global cement industry. Second, the benchmarking relies on literature-based inventory data that may differ in terms of data quality, reporting conventions, and background assumptions. Although harmonization of the functional unit and system boundary was applied, some residual differences are unavoidable.

Future research could extend the present analysis by including multiple cement plants, additional impact categories beyond climate change, and uncertainty or sensitivity analyses to assess the robustness of the results. Scenario-based assessments exploring the effects of clinker substitution, alternative raw materials, and carbon capture technologies would further enhance understanding of potential pathways for reducing the environmental impacts of clinker and cement production.

5. Conclusions

The main conclusions of this study are summarized as follows:

- A cradle-to-gate life cycle assessment was performed for clinker production at a representative integrated cement plant using real industrial operational data, with a functional unit of 1 t of clinker, enabling a plant-level evaluation under realistic operating conditions.
- The case-study plant exhibits lower thermal energy demand (3162 MJ/t clinker) and electricity consumption (52.23 kWh/t clinker) than the harmonized literature benchmark, indicating comparatively efficient kiln operation and auxiliary process performance.
- Despite the improved energy-related indicators, the total global warming potential of clinker production at the case-study plant (1010 kg CO₂-eq/t clinker) remains comparable to the benchmark value, demonstrating that reductions in energy consumption do not necessarily lead to proportional decreases in overall climate change impacts.
- Contribution analysis confirms that process-related CO₂ emissions from limestone calcination are the dominant source of greenhouse gas emissions, accounting for approximately 73% of the total global warming potential and largely determining the climate performance of clinker production.

- The benchmarking results highlight the importance of interpreting energy efficiency indicators in conjunction with emission source contributions, as benchmarking based solely on energy performance may lead to misleading conclusions regarding climate impact.
- Overall, the findings indicate that while continued improvements in energy efficiency and fuel management remain important, substantial reductions in greenhouse gas emissions from clinker production will require mitigation strategies that directly target process-related emissions, including clinker substitution, alternative raw materials, and carbon capture technologies.

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Abbreviations

The following abbreviations are used in this manuscript:

CCUS	Carbon capture, utilization, and storage
CO ₂	Carbon dioxide
FU	Functional unit
GHG	Greenhouse gas
GWP	Global warming potential
IPCC	Intergovernmental Panel on Climate Change
LCA	Life cycle assessment
LCI	Life cycle inventory
LCIA	Life cycle impact assessment
OPC	Ordinary Portland cement

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