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Benchmarking of Energy Consumption and CO_2 Emissions in Cement Production – A Case Study

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Abstract

In the pursuit of economic growth and value creation, foundation industries including cement, metals, glass, chemicals, paper and ceramics face formidable challenges related to energy usage, emissions, and resource consumption in their manufacturing operations, all while striving to achieve ambitious Net Zero carbon and green targets. To overcome these challenges and propel sustainable progress, benchmarking emerges as a powerful ally. This study performs a benchmarking analysis of energy use and CO_2 emissions for a UK cement plant as well as Best Available Techniques (BAT) investigation to identify opportunities for performance improvement in crucial areas such as energy usage and environmental sustainability. The research utilises industrial data from a 2850 tonne per day capacity dry process cement plant. Key energy and emissions parameters, including thermal and electrical energy intensity, recovered energy and CO_2 intensity, are computed per tonne of cement produced along with capacity utilisation across major process stages including raw material grinding, clinkerisation and cement grinding. Comprehensive data sourced directly from the manufacturer is compared against literature benchmarks for global averages and best practices. Although surpassing global average values, the plant lags European best practices across all metrics, signalling room for substantial improvement. Assessment of relevant BATs for the cement industry reveals prospects to integrate vertical roller mills for cement grinding and use Organic Rankine Cycle (ORC) at the clinkerisation stage. Adopting these techniques could reduce the electrical energy intensity of clinkerisation by 51% and cement grinding electrical intensity by 30%, surpassing benchmarks. While limited to a single cement plant, the study provides a standardised methodology that could be replicated across foundation industries to enable performance tracking and highlight efficiency gaps. The benchmarking approach developed can guide the implementation of energy conservation measures and the adoption of best practices by the cement industry to reduce its carbon footprint.

Keywords: Sustainable manufacturing; Benchmarking; Energy efficiency; Foundation industries; Net Zero.

1 Introduction

Foundation industries including cement, metals, glass, chemicals, paper and ceramics serve as crucial industries, generating wealth and significantly representing a nation's economy and overall strength. These industries provide £52 billion to the UK economy by producing 28 Mt of materials annually [1]. However, while meeting human demands through the production of goods and services, the foundation industries consume substantial amounts of limited energy and materials, often with low energy efficiency and resource conversion rates. This inefficiency leads to significant waste and severe environmental damage [2]. The foundation industries are responsible for around 10% of total CO_2 emissions [3]. Significant energy consumption and emissions growth have led to severe environmental pollution. The 2017 energy efficiency survey report indicates that the global demand for fossil energy continues to rise, resulting in a general increase of over 30% in global energy consumption [4]. Notably, the industrial sector is a major contributor to this escalating energy demand, accounting for more than 53% of the nation's total energy consumption [5]. In this context, it is critical for foundation industries to improve their environmental sustainability and reduce their resource consumption. Benchmarking is a powerful tool that helps industries identify and prioritise opportunities to improve energy efficiency and environmental sustainability [6–8]. This tool has been well-developed for more than 40 years, after first being used by Xerox Corporation in the early 1980s. Xerox's approach involved studying and learning from various industries, not just its direct competitors, in order to identify best practices and innovative strategies that could be applied to their operations [9].

The cement industry ranks as the third-largest consumer of industrial energy worldwide, responsible for approximately 7% of global industrial energy consumption and ~7% of global CO_2 emissions, faces particular challenges in achieving sustainability due to its inherent energy- and emissions-intensive production processes [10, 11]. Although the cement industry recognises the need to reduce its environmental impacts, benchmarking initiatives remain limited [12]. Global studies reveal wide variability in energy efficiency and carbon emissions between different cement plants, suggesting major potential for improvement through systematic benchmarking [12]. However, comprehensive data is lacking, as cement producers are often reluctant to share detailed operational insights.

This study focuses on benchmarking the energy usage and carbon emissions of a UK cement plant to pinpoint opportunities for enhancing efficiency and reducing environmental impacts. A tailored benchmarking methodology that incorporates BAT analysis has been developed to evaluate the cement plant's thermal energy intensity, electrical energy intensity, waste heat recovery, CO_2 intensity and capacity utilisation. Metrics are compared against industry best practices to highlight potential areas for improvement. The primary objective of this study is to enhance the sustainability of energy and emission intensive manufacturing processes, with a strong focus on environmental considerations and resource efficiency. Therefore, this study aims to achieve this by introducing a benchmarking approach, which offers a systematic method for evaluating and enhancing the sustainability of manufacturing systems. Ultimately, this endeavour is expected to foster the growth and advancement of the manufacturing industry while promoting environmentally friendly practices and resource conservation.

2 Benchmarking Approach Development

This section outlines the steps involved in the benchmarking approach development process and provides the rationale behind each step.

2.1 Understanding the Manufacturing Operations of Foundation Industries

A generic process model has been developed to elucidate the key elements involved in manufacturing operations across various foundational industries (Figure 1). This model illustrates the typical inputs and outputs that are inherent to production processes. Inputs encompass raw materials, electricity, and fuel, which provide the physical components, energy, and power needed to enable manufacturing activities. Outputs include the desired final manufactured products, as well as waste streams and carbon dioxide emissions, which tend to be unavoidable byproducts of industrial production.

A salient feature of the model is its illustration of process heat recovery as a key component. Many manufacturing processes intrinsically generate significant waste heat, which represents a loss of energy efficiency if not harnessed. Thus, incorporating heat capture and reuse into process designs can dramatically improve the energy efficiency and environmental profile of manufacturing. Additionally, the model highlights machine capacity utilization as a vital parameter in optimising industrial production. Running machines at maximum capacity boosts productivity and diminishes per-unit costs. However, energy, materials, and labour must be balanced to avoid inefficiencies associated with over-capacity.

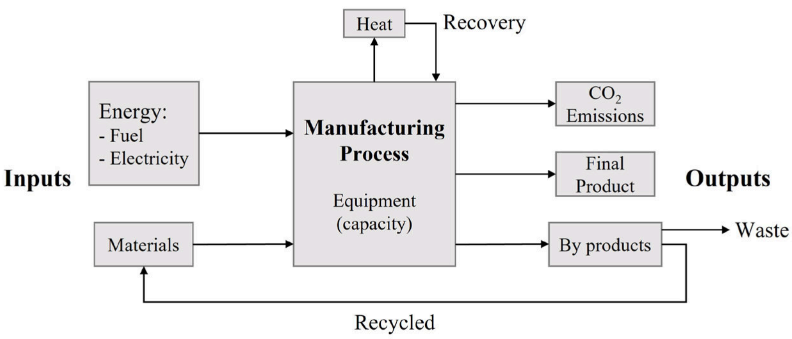


Figure 1 Generic manufacturing process model of inputs-outputs

2.2 Identification of Key Process Metrics

Both intensity and performance-based metrics have been utilised in this work to evaluate manufacturing efficiency from complementary perspectives. As noted by Jaller and Matthews [13], intensity-based measures that quantify emissions per unit output offer valuable insight into efficiencies, as declining emissions per product indicate improved environmental performance over time. Though intensity metrics do not directly correlate with overall emission reductions, they enable critical trend analyses. Furthermore, performance metrics that gauge the achievement of economic and regulatory targets are essential, as highlighted by Ogunsiji and Ladanu [14]. In a manufacturing context, performance indicators provide insights into operational performance while highlighting performance gaps and continuous improvement opportunities. Thus, this study employs intensity metrics for their utility in tracking efficiency gains, alongside performance metrics to assess broader goal attainment. This dual intensity and performance-based approach thereby enables a multidimensional assessment of manufacturing efficiency. The chosen metrics along with description and units are provided in Table 1.

Table 1 Vital sign metrics for manufacturing sustainability

Metric	**Description**	**Formula**	**Unit**
Thermal energy intensity	The amount of thermal energy used to produce a unit of output	(Thermal energy consumed) / (Unit mass Produced)	kWh/t
Electrical energy intensity	The amount of electrical energy used to produce a unit of output	(Electrical energy consumed) / (Unit mass Produced)	kWh/t
Energy recovered (heat)	The amount of energy recovered or reused from the process	(Recovered energy) / (Total energy waste)	%
CO_2 intensity	Total direct emissions per unit mass produced	(CO_2 emissions) / (Unit mass Produced)	tCO_2/t
Capacity utilisation	The extent to which production capacity is being used	(Actual output rate) / (Max possible output rate)	%

2.3 Data collection points

2.3.1 Industry data collection

Based on the selected metrics, a data template was developed to facilitate the benchmarking process, as shown in Table 2. This will capture and organise multiple entries, such as product type, equipment used, process conditions, process specification, and measurement methods used which is an important part of data collection.

Table 2 Data collection template

Process Data Form				
	Process			
	Product type			
	Equipment used			
	Process conditions			
	Process Specification			
	Metrics	Unit	Measurement Method	Current Value
1	Thermal energy intensity			
2	Electrical energy intensity			
3	Energy recovered			
4	Capacity utilisation			
5	CO_2 intensity			

The measurement method used to collect data affects the accuracy of the data. For example, collecting data using sensors on the machine or equipment (such as an energy meter) can provide more accurate data than using bill data or production output data. Additionally, it pinpoints the extent of the data presented, whether it directly results from the process or encompasses other aspects beyond the process (such as indirect emissions or auxiliary energy consumption). The current value represents the value provided by the manufacturer which was compared with the global average and best practice values.

2.3.2 Literature data collection

This section outlines the procedure adopted to collect essential data from the literature, comprising global average and best practice values, as well as best available techniques (BATs) and their associated impacts and costs. The gathered information is instrumental in assessing company performance, comparing it with industry standards, and exploring potential avenues for efficiency improvement. This establishes the basis for evaluating manufacturing processes and the potential adoption of BATs.

2.3.2.1 Global and best practice values

The procedure employed in this study follows a comprehensive approach to gather data concerning global average values, as well as best practice benchmarks, relevant to the various identified metrics. A literature review was conducted to collect relevant information from articles, industry reports, and government publications. The primary aim of this data collection was to establish a solid foundation for benchmarking the manufacturing processes under investigation. By analysing these averages and best practice standards, this study intends to assess company performance and compare operational data against industry norms, facilitating the identification of areas for potential improvement and efficiency enhancement.

2.3.2.2 BATs, their impact and associated cost of implementation

Within the approach, a thorough exploration of BATs for the manufacturing processes under scrutiny was undertaken. A comprehensive examination of BATs, including their associated impacts, as well as the estimated costs of implementation, was conducted. This analysis drew upon data derived from various studies, governmental bodies, and environmental agencies. The main objective of this analysis was to provide a comprehensive understanding of the potential benefits and economic implications associated with the adoption of BATs. By evaluating the feasibility and cost-effectiveness of BAT implementation, this study aims to assist companies in making informed decisions concerning process improvements, while also quantifying the resulting savings in energy consumption.

2.4 Developed Benchmarking Approach

The benchmarking approach adopted in this study (Figure 2) is structured around three key pillars. The first pillar involves an extensive literature review, which encompasses the collection of data on best practices, global averages, and BATs along with their associated environmental and cost considerations. The second pillar centres on the acquisition of industry-specific data, including production, processing, and equipment-related information within the manufacturing processes under examination. The final pillar revolves around data analysis, which includes the comparative assessment of industry data against benchmarks, an evaluation of the potential impact of best practices and BATs, and the estimation of cost savings. This holistic approach equips the study with the necessary insights to evaluate manufacturing processes objectively, identify areas for enhancement, and make informed decisions concerning efficiency improvements and sustainability.

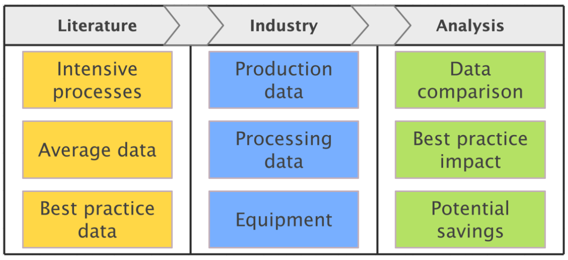


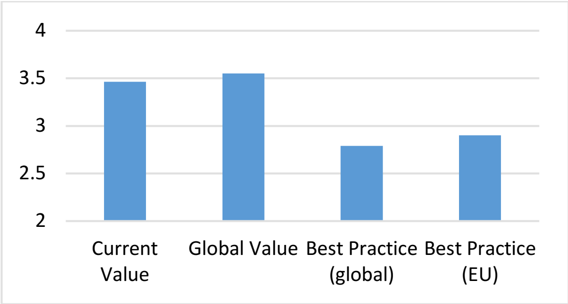
Figure 2 Benchmarking approach overview

3 Case study results and discussion

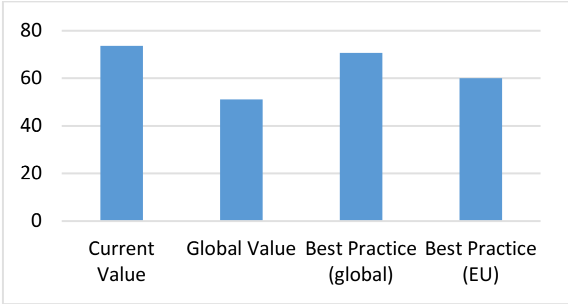
Utilising the developed benchmarking approach, a case study was conducted with a prominent cement manufacturer based in the UK having a plant capacity of 2850t/day. Notably, the cement manufacturing industry, one of the major foundation industries, stands as a significant consumer, demanding nearly 15% of the total industrial energy use due to its energy-intensive processes [15]. The case study reveals significant relevance for advancing sustainable practices within this vital sector.

3.1 Industry vs. literature metrics data

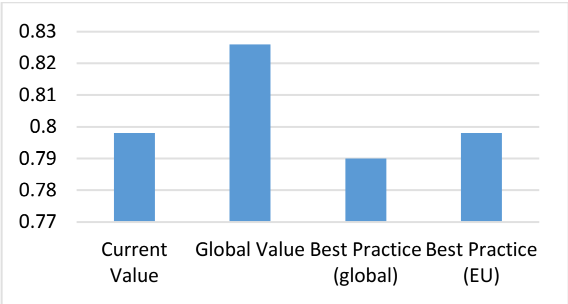
A detailed comparison was conducted between data sourced from the industry, employing the developed data collection template, and data obtained from the literature. The dataset encompasses three pivotal processes: raw meal grinding, clinkerisation, and finish grinding, collectively constituting 20%, 25%, and 40% of the total energy demand in cement production, respectively [16]. Specifically, the clinkerisation stage is scrutinized for thermal energy intensity, heat energy recovery, CO_2 intensity, and capacity metrics. In contrast, electrical energy intensity is analysed across all stages. The data are presented in Figure 3. This evaluation revealed that the performance of the plant in question surpasses global average values in all aspects for all stages. However, there is still room for improvement as their values fall short of best practice benchmarks both globally and in Europe.



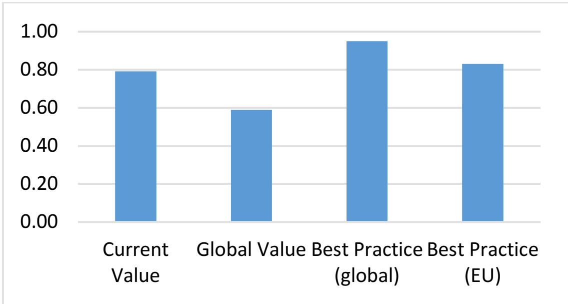
(a) Thermal Energy Intensity (GJ/t)



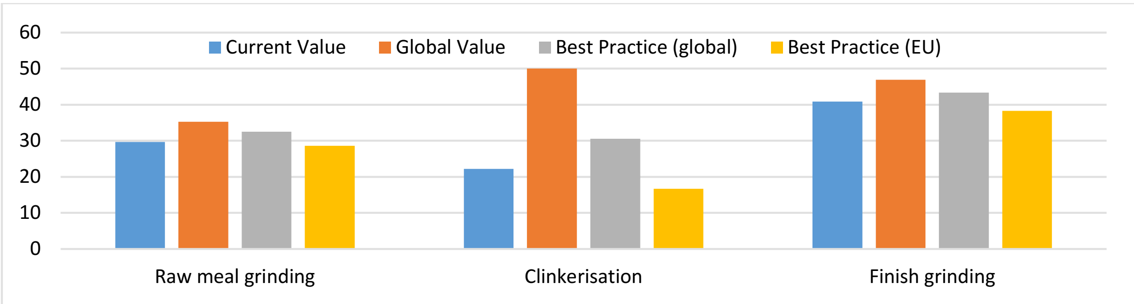
(b) Heat Energy Recovered (%)



(c) CO_2 intensity (t CO_2/t)



(d) Capacity utilisation (%)



(e) Electrical Energy Intensity (kWh/t)

Figure 3 Industry VS literature data visualisation. (a) to (d) represents the Clinkerisation stage only while (e) shows all three stages [16–26]

Note: The current values of all metrics i.e., thermal energy intensity, heat energy recovered, CO_2 intensity, capacity utilisation and electrical energy intensity are directly obtained from the industry.

3.2 BATs Identification and Analysis

The subsequent step entailed the acquirement of BATs relevant to cement manufacturing. Tackling energy consumption was prioritised and for this reason, BATs related to energy consumption were examined. This includes detailed data on their associated electrical and thermal energy savings, as well as implementation costs, sourced from literature. The dataset comprises BATs tailored to the three production stages, in addition to generic techniques with broader applicability across the entire cement plant. This compilation phase establishes the groundwork for the evaluation of potential improvements within the studied industry.

Table 3 Cement BAT, their energy impact and associated cost [27–31]

	BAT applicable to the cement sector (Energy)	Savings		Implementation Cost (M€)
		Electric (MJ/t)	Thermal (MJ/t)	
1	Replacing a ball mill with a vertical roller mill in raw material grinding	40	0	29.9
2	Use of gravity-type homogenising silo for raw material blending	10	0	6
3	Changing from long kilns to kilns with cyclone preheaters and pre-calciner	18	1800	85
4	Organic Rankine Cycle (ORC) for power generation through waste energy recovery	41	0	20

5	Changing from rotary or satellite coolers to modern grate coolers	-18	200	17.5
6	Using 5 or 6 stage cyclone preheater	0	90	6.5
7	Replacing ball mills with vertical roller mills in cement grinding	43	0	25
8	Using high efficiency separator for cement grinding	12	0	1.5
9	Using variable speed drives for all fans	6	0	0.16
10	Introduction of process control optimisation (Advanced plant control systems)	8.5	95	2.6
11	Replace low efficiency motors with premium and super premium efficiency motors (IE3 and IE4)	14.5	0	0.5
The negative sign (-) denotes an increase in energy consumption cause by implementing a technology.				

3.3 Industry BAT adoption and impact

Following the identification and assessment of the applicable BATs employed by the company, a commendable adoption of many recognised techniques was revealed. Nevertheless, two notable exceptions emerged. The first pertains to the untapped potential of harnessing power through waste energy recovery at the clinkerisation stage, a prospect offered by the Organic Rankine Cycle (ORC). The second involves the integration of vertical roller mills (VRM) for cement grinding, showcasing opportunities for further refinement in the company's manufacturing processes.

The potential energy intensity values are computed based on the savings conceivable by adopting the lacking BATs and compared to the best practice values. In the case of clinker production, the potential electrical intensity could be reduced by 51%. Furthermore, utilising VRM for cement grinding could potentially reduce the electrical energy consumption by 30%. This will allow the company to surpass best practice energy use values, as shown in Figure 4.

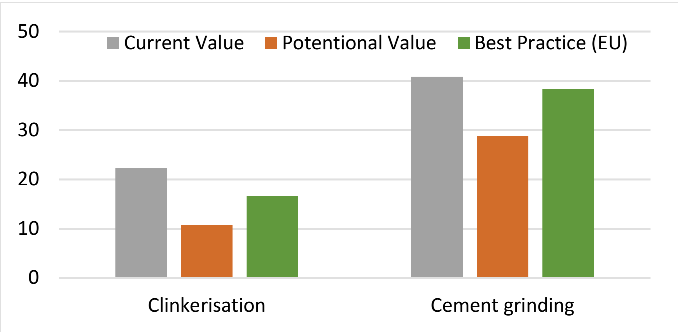


Figure 4 Current and potential electrical energy values (kWh/t) comparison

The potential total energy savings of each stage have been compared with the implementation cost of the identified BATs. As seen from Figure 5, it is evident that the BAT for clinker production incurs lower implementation costs but yields less energy savings. However, the additional EUR 5 million needed for implementing the cement grinding BAT may not justify the possible 0.5 kWh/t extra savings. Therefore, implementing ORC for energy generation maybe the more economical option.

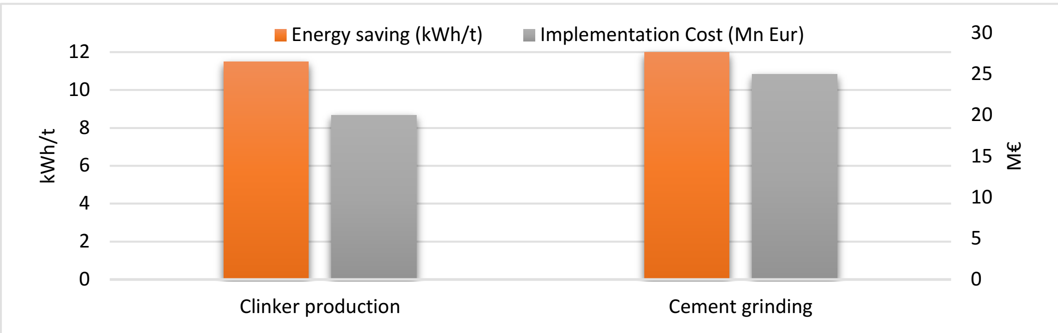


Figure 5 Energy saving (kWh/t) VS Cost (M€)

4 Conclusion

This study demonstrates the value of benchmarking as a tool for assessing and improving the energy efficiency and carbon footprint of energy-intensive manufacturing processes, using a UK cement plant as a case study. The benchmarking analysis quantified the plant's energy intensity and CO_2 emissions per tonne of cement produced across key process stages including raw material grinding, clinker production, and cement grinding. Performance gaps were revealed relative to current global averages and best practices.

The study also compiled relevant best available techniques (BATs) for the cement sector, revealing additional prospects to integrate vertical roller mills for cement grinding and use Organic Rankine Cycle to increase waste heat recovery. Adopting these BATs could reduce the electrical energy intensity of cement grinding by 30% and clinkerisation by 51%, surpassing global benchmarks. A preliminary economic analysis further showed clinker production improvements may offer a more economical energy saving option. This is due to the considerably lower implementation cost (EUR 5 million) while providing a relatively similar energy saving potential (±5 kWh/t).

Overall, this research demonstrates the usefulness of a benchmarking procedure that incorporates BATs for cement manufacturers to identify performance gaps, best practices, and efficiency opportunities. Although limited to a single cement plant, the standardised methodology could be replicated across multiple sites to support step-change improvements industry wide. The approach could also be adapted to enhance sustainability in other foundation industry sectors.

The study acknowledges certain limitations in its methodology. While BATs affecting energy consumption are thoroughly examined, their impact on emissions is not included in this analysis. Additionally, while energy savings are compared to initial implementation costs, long-term cost-effectiveness is a factor that warrants further consideration. Moreover, the study considers the cost of implementation in a generalised sense, without delving into the specific costs that may be influenced by plant layout and other site-specific factors. These limitations serve as areas for potential refinement and consideration in future analyses.

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