International Journal of Thermodynamics (IJoT)
ISSN 1301-9724 / e-ISSN 2146-1511
https://dergipark.org.tr/en/pub/ijot

Vol. xx (No. x), pp. xxx-xxx, 2025
doi: 10.5541/ijot.1572561
Published online: Mmm dd, 2025

Review Article

A Literature Review on Energy, Exergy, and Exergoeconomic Analyses in Cement Rotary Kilns

[1*]E. Kodanli, [1] İ. Uzun

[1]Faculty of Engineering and Natural Sciences, Kırıkkale University, Ankara Road 7th km, 71450, Kırıkkale, Turkey
E-mail: *evrenkodanli@gmail.com

Received 27 November 2024, Revised 4 June 2025, Accepted 1 July 2025

Abstract

The cement production industry is one of the most energy-intensive sectors globally, with energy costs constituting approximately 30-40% of total production expenses. Among the various stages of cement production, the rotary kiln process is particularly energy-intensive, making its efficiency a critical factor in reducing energy consumption and environmental impact. This article offers a comprehensive review of previous studies on energy analysis, exergy analysis, exergy balance, exergy efficiency, and exergoeconomic analysis in the cement industry. The reviewed studies indicate that exergy efficiencies in cement production units vary between 16% and 67%, with significant exergy losses occurring in the rotary kiln due to its irreversible nature. The primary objective of this study is to consolidate findings from the literature, providing a more comprehensive understanding of energy and exergy flows in cement production processes. By identifying key trends, gaps, and opportunities for improvement, this review aims to make a significant contribution to energy savings and sustainability in the cement industry. The findings emphasize the potential of strategies such as waste heat recovery, the use of alternative fuels, and advanced process optimization techniques to enhance energy efficiency and reduce environmental impacts. However, the review also identifies a significant gap in the literature: the lack of integration of advanced optimization techniques, such as artificial neural networks (ANNs) and the Taguchi method, into cement production processes. These techniques have demonstrated significant potential in other industrial sectors but remain underexplored in the context of cement rotary kilns. This study proposes the integration of these advanced methods as an innovative approach to further enhance energy efficiency and sustainability. In conclusion, this review not only consolidates existing knowledge but also offers a roadmap for future research and industrial applications. By addressing the identified gaps and implementing the proposed strategies, the cement industry can transition towards more sustainable and energy-efficient production processes, contributing to global efforts to reduce energy consumption and greenhouse gas emissions.

Keywords: *Cement factory; thermal analysis; environmental sustainability; rotary kiln; energy and exergy efficiency; literature review.*

1. Introduction

In today's world, cement production is becoming increasingly important due to the rapid growth of the construction sector and evolving infrastructure needs. Cement is a fundamental material used in construction and represents a significant industrial sector worldwide. However, cement production is one of the most energy-intensive industries, with energy costs accounting for approximately 30-40% of total production costs. Among the various stages of cement production, the rotary kiln process is the most energy-intensive stage. Therefore, improving the energy efficiency of rotary kilns is essential for reducing production costs and enhancing sustainability in the cement industry.

To address the high energy consumption in cement production, energy, exergy, and exergoeconomic analysis methods have been widely used. These methods aim to optimize energy consumption, identify inefficiencies, and improve overall production efficiency. Exergoeconomic analysis, in particular, serves multiple purposes:

(i) Calculating the cost of each product in a system with multiple outputs separately,

(ii) Understanding the cost flow and structure of the system,

(iii) Identifying specific variables of the system's fundamental elements and optimizing these variables,

(iv) Taking the system as a whole and performing its optimization [1].

These analyses are essential for identifying energy losses, improving process efficiency, and reducing environmental impacts.

Global cement production, which was 4.4 billion tons in 2021, decreased to 4.1 billion tons in 2022, representing a 6.82% decline [2]. This decrease is attributed to the COVID-19 pandemic experienced worldwide. However, it is expected to increase by approximately 25% by 2030, driven by growing infrastructure demands. This anticipated increase underscores the importance of reducing CO_2 emissions in cement production. CEMBUREAU (The European Cement Association) aims to align with the Paris Agreement by reducing CO_2 emissions by 30% in the first stage and by 40% in the second stage by 2030 [3]. Cement production must therefore focus on energy efficiency, emission reduction, and sustainable practices, including the use of alternative fuels and carbon capture technologies. These technologies could lead to a 39% to 78% reduction in lifecycle greenhouse gas emissions [4]. Energy consumption will be optimized, reducing CO_2 emissions through innovative technologies such as waste heat recovery and alternative fuels.

Despite numerous studies on energy and exergy analyses in cement production, there is a significant research gap in the integration of advanced optimization techniques such as artificial neural networks (ANNs) and the Taguchi method. These methods have shown great potential in other industrial sectors for optimizing energy consumption and process efficiency, but their application in cement rotary kilns remains underexplored. This study aims to address this gap by proposing a framework for integrating these advanced techniques into cement production processes, thereby providing a more comprehensive approach to energy efficiency and sustainability.

The classification of energy and exergy analyses in cement production is conducted to better understand and optimize energy use and losses at different stages of the process. This classification allows for the separate evaluation of energy and exergy efficiencies of the main components in the cement production process (e.g., grinding, calcination, clinker production, and cooling). By doing so, the stages with the highest energy losses can be identified, and improvement strategies can be developed for these stages. For example, while energy analysis measures the overall energy consumption and efficiency of the process, exergy analysis evaluates the quality and usability of energy, identifying irreversible energy losses (irreversibility). This classification is critical for achieving energy savings and reducing environmental impacts in cement production.

Cement production processes such as raw material calcination and clinker production require high temperatures and are carried out in rotary kilns. Rotary kilns are suitable for using both fossil fuels (e.g., natural gas) and alternative fuels (e.g., waste oils, tires, biomass). The energy efficiency of rotary kilns and the reduction of exergy destruction are essential for sustainable cement production. Energy-exergy-exergoeconomic analysis methods play a crucial role in optimizing energy consumption and increasing production efficiency in cement factories. These methods involve a series of analyses and calculations used to identify energy losses, improve fuel efficiency, and recover waste heat.

In today's world, conventional energy sources are rapidly depleting, and energy costs are increasing. The industrial sector accounts for approximately two-fifths of total final energy consumption in most countries. Energy consumption in the industrial sector is closely linked to the availability of resources and the current state of industrialization. As depicted in Figure 1, industrial facilities with high energy consumption primarily rely on fossil fuels, with minimal input from renewable energy sources. The majority of the incoming energy is used in high-temperature processes, such as those in cement production, with a small portion utilized in lower-temperature industries. In all sectors, the generation of products and waste outputs is an inevitable outcome [5].

This study offers a novel contribution to the literature by consolidating findings from various energy, exergy, and exergoeconomic analyses in cement rotary kilns. Unlike previous reviews, this work not only summarizes existing research but also identifies critical gaps, particularly the lack of integration of advanced optimization techniques such as artificial neural networks and the Taguchi method in cement production processes. By highlighting these gaps, this study paves the way for future research aimed at enhancing energy efficiency and sustainability in the cement industry.

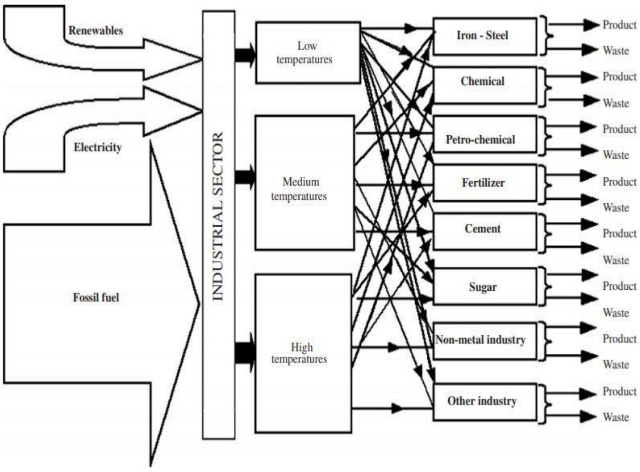

Figure 1. Energy flows in the industrial sector [5].

Studies related to energy and exergoeconomic analysis in cement plant rotary kiln processes are classified into the following headings:

Energy And Exergy Analyses;

Energy and exergy analyses focus on analyzing the energy consumption and exergy losses of the process to enhance process efficiency. These analyses determine the potential for improving the energy efficiency of the process and ensure more effective utilization of resources. Exergy is known as a measure of the maximum usability of the potential energy contained within a system relative to a reference state [6]. Exergy is also known in terms of available energy, availability, technical work capacity, available energy, and work potential [6].

Studies based on fuel type have focused on the effects of using different fuel types in the rotary kiln process. Fossil fuels are commonly used in the cement industry due to their availability and price. In recent years, concerns about rising prices and climate change have led the cement industry to explore alternative fuel sources that can partially or completely replace fossil fuels [7]. The use of different fuel types such as coal, natural gas, and waste fuels can be investigated to evaluate process performance and environmental impacts.

Studies related to energy and exergoeconomic analysis in cement plant rotary kiln processes are categorized into various topics as follows:

Furnace Design and Operational Parameters;

Studies in this area aim to determine the effects of different furnace design options and operational parameters on the rotary kiln process. Operating parameters refer to parameters such as kiln temperature, combustion air flow, fuel type, rotary kiln speed, coal feed rate, etc. Furnace model analysis involves defining tasks and analyses for the calculation of a cement rotary kiln. General procedures for furnace modeling include:

Structural modeling of the rotary kiln using finite element methods.

Static nonlinear analysis of a complete model. Dynamic linear analysis of a fully modified model.

Determination of furnace body dimensions according to structural verification, including fatigue and ovalization, based on ASME standards [8].

Control Strategies;

Control strategy studies aim to examine the management and performance of the rotary kiln process using automatic control systems. These studies enable the process to operate at desired parameters and improve efficiency.

Clinker Quality;

Clinker quality is primarily determined by the characteristics of the furnace feed and the thermodynamic conditions of the furnace. Therefore, stable control of the chemical compositions of the furnace feed and the thermodynamic profile of the facility is a primary requirement [9].

Renewable Energy Studies;

Studies on renewable energy explore the use of renewable energy sources in the rotary kiln process. Such studies focus on topics such as solar energy, wind energy, and biomass energy. Cement plants generally focus on efficient use of electricity within the facility to avoid emissions [10]. However, cement plants are increasingly purchasing and using more green energy sources in production [10], generated from wind and solar energy facilities. This enables cement plants to reduce CO_2 emissions in cement production.

Economic Analysis;

Economic analysis studies aim to reduce costs during the rotary kiln process. Factors such as optimizing furnace parameters, reducing energy consumption, and recovering waste heat aim to increase economic efficiency. Exergoeconomic analysis combines economic and exergy analyses. Through thermo-economic analysis, the cost ratio of exergy consumption and exergoeconomic performance parameters (i.e., relative cost difference and exergoeconomic factors) are determined, aiding in indicating how resources can be used more efficiently to conserve resources [11].

Cement Quality Improvement Studies;

Studies to improve cement quality during the rotary kiln process involve optimizing furnace parameters, improving raw material quality, and developing operational strategies.

While there are various topics covered in studies related to cement rotary kilns, one of the most notable areas in recent years is the use of alternative fuels. Traditionally, the cement industry fuels rotary kilns using fossil fuels such as coal. However, rising energy costs, environmental concerns, and the limited availability of fossil fuels have popularized the use of alternative fuels. Alternative fuels can be sourced from various materials such as industrial waste, rubber, plastics, biomass, and petrochemical by-products. These fuels are both environmentally sustainable and cost-effective. However, the use of alternative fuels can complicate furnace operational parameter control and emissions control. Numerous studies are evaluating the impact of alternative fuel usage, covering topics such as alternative fuel preparation technologies, combustion behavior, emissions, optimization of furnace operational parameters, and the economic effects of alternative fuel usage. The use of alternative fuels is considered a significant topic for the cement industry, and further research is expected in the future [10].

The rotary kiln process in cement plants, being a thermal process occurring at high temperatures, can result in significant exergy losses at elevated levels. These losses occur across all components of the process. Exergy analysis allows for the determination of energy consumption and losses for each component, enabling the identification of suitable methods to enhance process efficiency. This analysis not only assists in improving process efficiency but also can reduce energy consumption. This leads to energy savings in cement plants, providing economic and environmental benefits.

Rotary kiln energy analysis considers factors such as different fuel types, process conditions, and various parameters of the process (e.g., temperature, air flow rate). The analysis results provide recommendations to enhance process efficiency. These recommendations may include the installation of energy recovery systems, improvement of fuel type and quality, optimization of thermal process parameters, and regulation of internal air flow within the kiln.

In conclusion, exergy analysis of rotary kilns in cement plants is an important tool for enhancing process efficiency. This analysis identifies energy consumption and losses in each component of the process, guiding efforts to optimize energy usage and minimize inefficiencies.

2. Literature Review

This study provides a comprehensive compilation of key topics related to energy efficiency, heat recovery, and rotary kiln systems within the cement industry. The objective is to focus on studies aimed at reducing energy consumption and achieving sustainability in cement production. This section contributes valuable insights by analyzing information and research in detail, particularly regarding efforts related to energy efficiency and environmental sustainability in the cement industry. Additionally, it will cover significant findings in the literature related to methods proposed for energy savings in rotary kiln systems, heat recovery technologies, and thermodynamic analyses. This literature review is intended to contribute to advancements in energy efficiency and environmental sustainability within the cement industry.

When energy is evaluated solely from a quantitative perspective, important data can be obtained; however, it remains deficient in terms of qualitative aspects. Therefore, it is necessary to use the exergy method to examine systems qualitatively. Various definitions of exergy are presented in Table 1.

This table provides a comprehensive overview of various definitions of exergy found in the literature. Exergy is a critical concept in thermodynamic analyses, as it measures the maximum useful work that can be extracted from a system. Different authors have defined exergy in slightly different ways, and this table consolidates these definitions to provide a clear understanding of the concept.

Gürtürk and Öztop [24] conducted thermodynamic and numerical analyses of industrial furnaces where thermal processes for gypsum production are carried out. After conducting a preliminary analysis on the old perlite furnace in the examined facility, they determined that the cylindrical body, chimney, upper, and lower cone parts were not insulated, which negatively affected combustion efficiency and kinetics due to direct deposition of raw perlite onto the flame created by the burner. Additionally, they found that the automation system of the furnace was inadequate. They conducted the energy analysis independent of reference

Table 1. Different definitions of exergy in the literature [12].

Researcher	Definition of Exergy
Rant [13]	Unknown Exergy is expressed as the ability of a specific portion of energy to be completely converted into another type of energy.
Szargut [14] Szargut et al. [15]	Unknown Exergy is a measure of the quality of different forms of energy and is defined as the amount of work that can be performed when the general substances in nature reach thermodynamic equilibrium.
Kotas [16]	Unknown Any equivalent work to any form of energy is a measure of its exergy and defines the maximum work obtainable using environmental parameters as a reference.
Shukuya [17]	Unknown While entropy expresses the distribution of energy and matter, exergy measures the potential distribution of energy and matter.
Sakulpipatsin [18] Bejan [19]	Unknown Exergy represents the theoretical minimum useful work required for a substance from the environment or a certain amount of substance to be converted into another form or specific state.
Connelly et al. [20]	Unknown Exergy defines the maximum work obtainable when a source reaches equilibrium with its surroundings through a theoretically reversible process.
Honerkamp [21]	Unknown The maximum portion of an energy form that can be converted into work is called exergy; the remaining portion is known as anergy.
Tsatsaronis [22]	Unknown The exergy of a thermodynamic system defines the theoretical maximum useful work obtained only when the system is in complete equilibrium with its thermodynamic surroundings during the interaction process.
Cengel et al. [23]	Unknown In everyday life, a person's exergy can represent the best work that person can do under the most favorable conditions.

environmental conditions. Energy analysis was compared between the new and old perlite furnaces, and the results were presented in Figure 2.

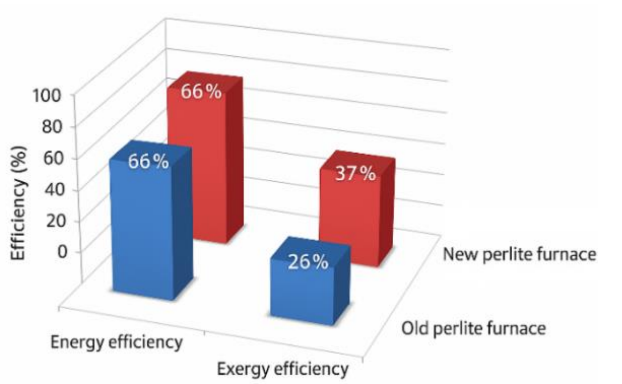

Figure 2. Comparison of new and old perlite furnaces [24].

They determined that the energy efficiency of the new perlite furnace is higher than that of the old perlite furnace. Despite insufficient insulation, it is observed that the new perlite furnace has an effect that could affect its energy efficiency. However, they found that energy losses resulting from inadequate insulation and air-fuel ratio negatively affected energy efficiency. They concluded that the reason for the small difference in energy efficiency between the new and old perlite furnaces is the high energy losses due to inadequate insulation and air-fuel ratio.

Altınkaynak et al. [25] conducted an energy and exergy analysis of the rotary kiln used in cement factories. They used a 130-ton capacity rotary kiln in their study. Utilizing factory data, they created separate mass balances and applied the first law of thermodynamics, considering input pressure, output pressure, input temperatures, and output temperatures. In the study, they recommended preventing the ingress of leakage air into the kiln, as they noted that leakage air entering the kiln would result in energy loss. They calculated the energy efficiency as 58.6% and the exergy efficiency as 49.2%.

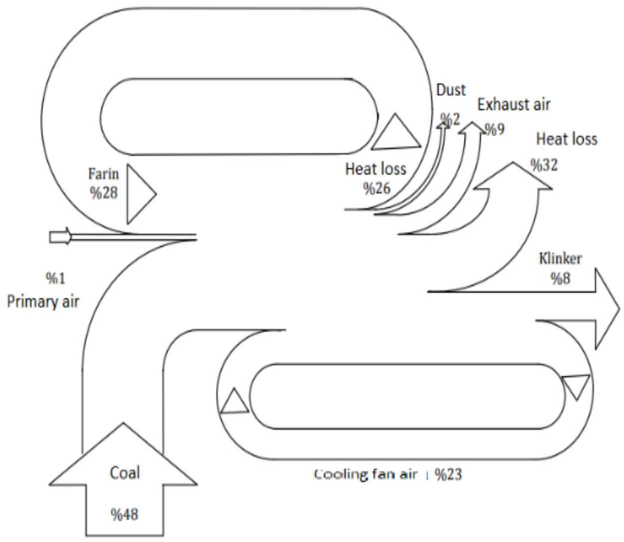

Figure 3. Sankey diagram showing energy flows in a rotary kiln [25].

According to the Sankey diagram shown in Figure 3, the largest input comprises 48% coal and 28% limestone. Additionally, 31% of the energy used in cooling the clinker comes from the cooling air entering the rotary kiln. After transferring the clinker energy to the cooling air, it is obtained as 8%. This illustrates the energy transfers in more detail. They have determined that 9% of the total energy exiting the system is waste air emitted from the electrostatic filter unit stack. This waste air can be reheated and reused, enabling steam production through an exchanger.

According to the Grassman diagram shown in Figure 4, the exergy efficiency of the rotary kiln was determined to be 49.2% based on the analysis and calculations. Coal represents 58% of the exergy input, while the exergy of the cooling fan air accounts for a 20% share for combustion and clinker formation. In the diagram, it is observed that the exergy obtained from the clinker is 6%, while the amount of lost exergy is 41%.

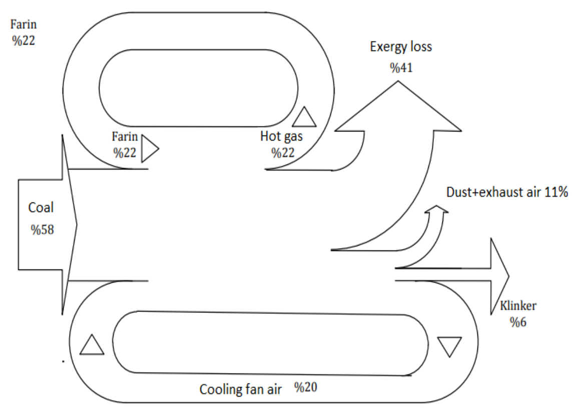

Figure 4. Rotary kiln grassman diagram [25].

Madlool et al. [26] conducted a study focusing on energy and exergy analyses in the cement industry. They conducted both physical and chemical exergy analyses.

Exergy is a method of measuring the available energy of a system and can be categorized into different types such as physical exergy, kinetic exergy, and chemical exergy. When considering all systems, they determined that the highest exergy loss occurs during the clinker production stage.

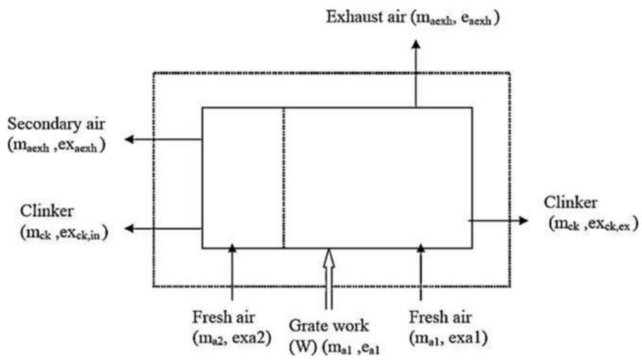

Figure 5. Mass and exergy flow diagram of the clinker cooler [26].

They found that the exergy efficiencies of cement production units range from 18% to 49% and also observed that the exergy losses due to irreversibilities in the kiln are higher compared to other units in the cement production facility. Various exergy flow types, including thermo-mechanical exergy, chemical exergy, heat flow exergy, and radiation exergy, indicate different forms of exergy flows. These different exergy flows can be represented in a diagram to visualize the energy flow within the system.

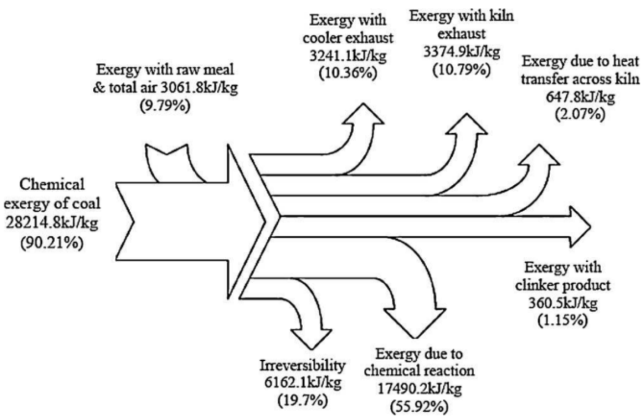

Figure 6. Exergy diagram for furnace system [27].

In the summary of the study, regarding exergy analysis, exergy balance, and exergy efficiency in the cement industry:

- Despite the highest energy efficiency for the raw mill, they found that the exergy efficiency remained below 26%, with the slag mill having the lowest exergy efficiency within the cement plant.
- Exergy efficiencies and irreversibility ranged from 18% to 49% and from 136.22 to 607.89, respectively, showing that the exergy efficiency values in the cement industry are inversely proportional to the dead state temperatures.

In their study [28], they conducted an energy and exergy analysis of the rotary kiln used for gypsum production. The rotary kiln configuration for clinker production in the cement industry is shown in Figure 7.

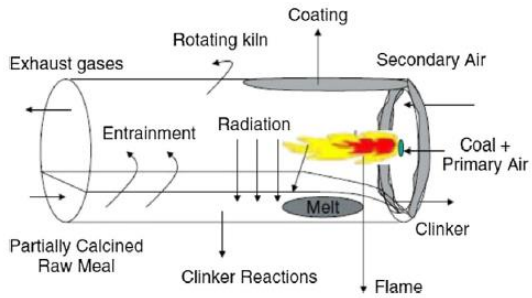

Figure 7. Schematic diagram of rotary kiln configuration [29].

The study indicates that complete combustion occurs, with both inlet and outlet being at atmospheric pressure, and the total mass change remains constant. Energy efficiency is calculated as 69%, while exergy efficiency is 16%. The analysis is based on the measured values of the rotary kiln, and energy and exergy efficiencies are calculated accordingly. The study explores the application of exergy analysis in various rotary systems and provides equations for calculating exergy efficiency with specific standard chemical exergy.

Koroneos et al. [30] conducted energy and exergy analyses to reduce energy costs and environmental impacts in cement and concrete production. The exergy balance of the process, including the calculation of exergy losses and exergy efficiencies, is depicted in the diagram presented in Figure 8, which illustrates the generalized exergy balance based on Koroneos et al. [30].

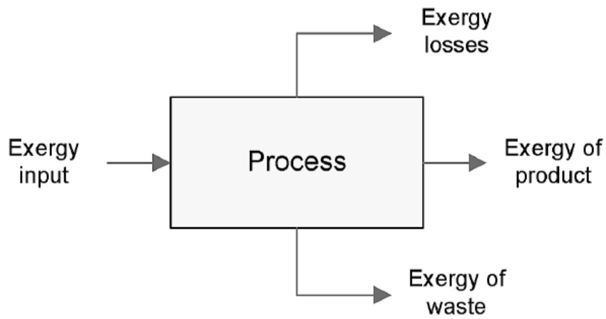

Figure 8. Exergy balance [30].

The energy efficiency was calculated as 68.5%, and the exergy efficiency was calculated as 30.9%. In the study, energy and exergy analyses of different stages in the cement production process were conducted, and energy and exergy flows were depicted on Sankey and Grassmann diagrams.

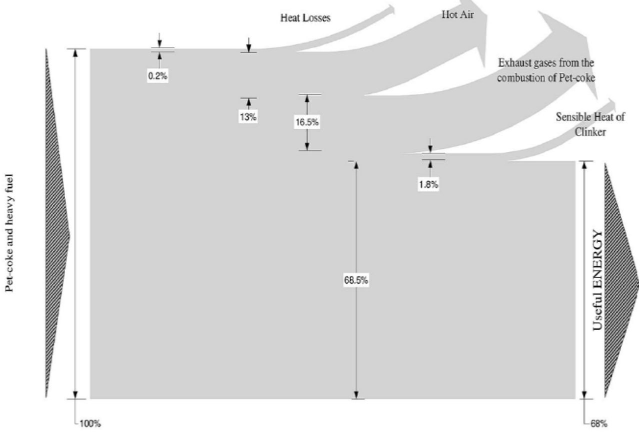

Figure 9. Energy balance sankey diagram [30].

As can be seen from the Sankey diagram, it was determined that a significant portion of the exergy loss originates from the cooling of the clinker (30.60%) and from the exhaust gases resulting from the combustion of petcoke (15.1%).

Madlool [31] the analysis of the waste gas and dust preheating system for a cement production facility in Iraq was carried out. The study analyzed four separate cyclones. The waste gas and dust preheating system is designed to control the temperature of exhaust gases from the preheating tower of the cement kiln and the dust load. These systems were installed to prevent accumulation and blockages in the preheating tower and to increase energy efficiency. It was determined that the proper design, installation, and maintenance of the systems are crucial; otherwise, efficiency may decrease, leading to operational issues.

Çamdalı et al. [32] energy and exergy analyses were performed on dry type rotary kiln systems using the first and second laws of thermodynamics to calculate efficiency.

$$\sum m_{in} = \sum m_{out} \tag{1}$$

$$\sum m_{in} = m_{farine} + m_{coal} + m_{air} \tag{1.1}$$

$$\sum m_{out} = m_{clinker} + m_{dust} + m_{s-gases} \tag{1.2}$$

$$Q_{cv} + \sum_{in} m_{in} \left(h_f^0 + \Delta h + \frac{v_{in}^2}{2} + g_G Z_{in}\right) = W_{cv} + \sum_{out} m_{out} \left(h_f^0 + \Delta h + \frac{v_{out}^2}{2} + g_G Z_{out}\right) + Q_L \tag{2}$$

In the study recommendations, it was noted that reducing thermal losses of the rotary kiln is possible through insulation. The importance of energy loss in exhaust air was emphasized. It was mentioned that controlling the amount of air entering the rotary kiln enables control of this energy loss. Energy efficiency was calculated as 97%, and exergy efficiency as 64.4%, assuming the system is in a steady state and continuous flow process.

In the study conducted by Farag, the energy and exergy efficiencies of a cement factory in Egypt were examined.

Specific physical exergy;

$$ex_{ph} = (h - h_0) - T_0(s - s_0) \tag{3}$$

In case of constant specific heat and ideal gas;

$$ex_{ph} = c_p(T - T_0) - T_0(c_p ln\frac{T}{T_0} - Rln\frac{P}{P_0}) \tag{4}$$

For solid and liquid flows;

$$ex_{ph} = c_p((T - T_0) - T_0 ln\frac{T}{T_0}) - v(p - p_0) \tag{5}$$

Chemical exergy;

$$ex_{ch} = sum\ of\ xi\ (ex_{ch} + RT_0 \ln(x_i)) \tag{6}$$

Using thermodynamic first and second law analyses, they calculated the energy efficiency to be between 41.6% and 51.5%, and the exergy efficiency to be between 26.8% and 35.6%. They suggested replacing the rotary cooler at the outlet of the rotary kiln with a grate cooler, indicating that this would provide more efficient heat recovery. The amount of raw mixture used in the process is 1.728 kg to produce 1 kg of clinker and 0.109 kg of by-pass dust. The quantities of different minerals formed in 1 kg of produced clinker and 0.109 kg of by-pass dust were provided. They determined the useful heat and exergy consumed by 1 kg of produced clinker to be 1729.8 kJ and 1187.7 kJ, respectively.

In their study [1] examined the rotary kiln process of a cement factory located in Balıkesir. They analyzed the rotary kiln as a whole and calculated the exergetic efficiency of the system using the PRECO (Product Exergetic Cost) method. They calculated the energy efficiency as 58.79% and the exergy efficiency as 44.8%. They also suggested that an adaptive interval multi-objective genetic algorithm type "ARMOGA", along with the genetic algorithm method, could increase the exergy efficiency of the system to around 47.57% levels and reduce unit costs. In conventional algorithms, the search domain is defined by extreme boundary limits, and all possible configurations within the data space are considered. The ARMOGA algorithm, however, narrows down feasible and infeasible parameter regions within the data space and generates a concentration of optimal solutions within these confined boundaries. Therefore, by utilizing denser and more efficient data, it has been shown to have a positive effect on improving exergy efficiency [1].

Sheinbaum and Ozawa [34] evaluated the energy usage levels and emission data from flue gases of cement factories in Mexico based on data from 1982 to 1994. They focused on various factors such as density, clinker activity, cement/clinker ratio, and the use of waste tires as alternative fuels. They found that changes in all factors except clinker activity led to a decrease in fuel usage. Overall, the study provided predictions regarding energy usage and CO_2 emissions in Mexico's cement industry. They suggested that reductions could be achieved through improvements in waste heat recovery from the system's waste and enhancements in the system's chimney and filters. They concluded that reintroducing waste heat back into the system could result in a 28% energy recovery and a 17.2% decrease in emission data from flue gases.

Osuolale and Osuolale [35] conducted an energy and exergy analysis for a cement production facility. They determined the energy and exergy efficiency of different stages of cement production and assessed the energy-saving potential of the facility. They calculated the exergy efficiency as 46.85%. Performance evaluations were conducted for different preheater and calciner systems, and recommendations were made to increase the energy efficiency of the facility. The HYSYS program was used to simulate the system and determine the thermodynamic properties of each system. The data used for simulation were obtained from the Lafarge Cement Plant.

Using simulation, they added known components and created components that were required but not available in the software. A series of reactions involved in the process were added based on simulation, and some of these reactions are represented in the following equations.

$$CaCO_3 \longrightarrow CaO + CO_2 \tag{7}$$

$$3CaO + Al_2O_3 \longrightarrow Ca_3Al_2O_6 \tag{8}$$

$$2CaO + SiO_2 \longrightarrow Ca_2SiO_4 \tag{9}$$

$$Ca_2SiO_4 + CaO \longrightarrow Ca_3SiO_5 \tag{10}$$

$$Ca_3Al_2O_3 + CaO + Fe_2O_3 \longrightarrow Ca_4Al_2Fe_2O_{10} \quad (11)$$

$$C + O_2 \longrightarrow CO_2 \quad (12)$$

$$4H + O_2 \longrightarrow 2H_2O \quad (13)$$

$$S + O_2 \longrightarrow SO_2 \quad (14)$$

Uğur et al. [36] identified the stage where energy losses occur to effectively save energy and proposed alternative methods for recovering these lost energies.

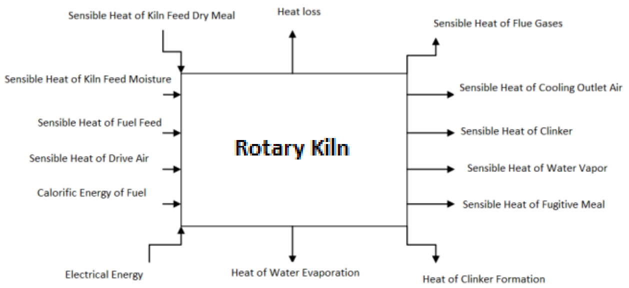

Figure 10. Rotary kiln flow chart [36].

Using thermodynamic first and second law analyses, they calculated the energy efficiency as 62% and exergy efficiency as 36%, emphasizing the importance of ensuring tightness in the rotary kiln process. The energy and exergy efficiencies resulting from their analysis are presented in Figures 11 and 12.

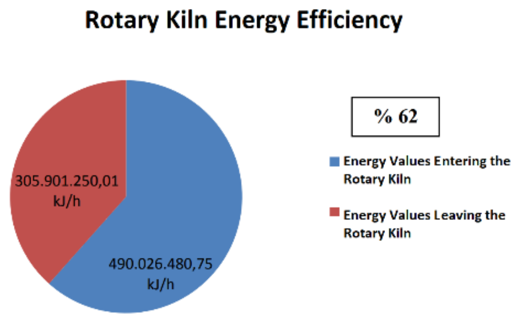

Figure 11. Rotary kiln energy efficiency [36].

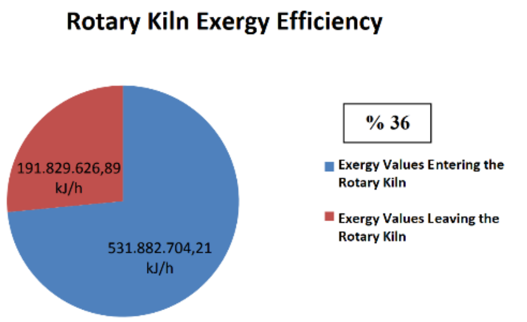

Figure 12. Rotary kiln exergy efficiency [36].

They observed that if tightness is not fully ensured, continuous leakage of air and farin occurs outside, which also reduces efficiency. Additionally, they emphasized the importance of paying attention to the properties of the coal fed into the rotary kiln and preferring coals with high combustion efficiency.

Altınkaynak et al. [37] in their study, energy savings and mass and energy balances for the rotary kiln process were established. Energy efficiency was calculated as 58.6%. In the Sankey diagram, they observed that the largest input consisted of coal, accounting for 48%, followed by 28% from limestone.

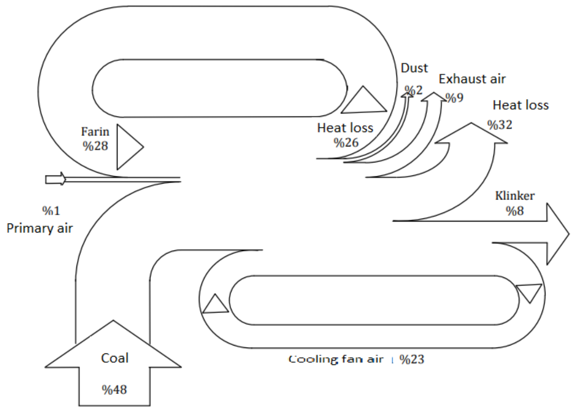

Figure 13. Rotary kiln sankey diagram [37].

Here, they found that the energy of the limestone originated from the hot gas drawn from the rotary kiln by the exhaust fan. From the Sankey diagram, it was determined that the energy used in cooling the clinker and the energy from the cooling air entering the rotary kiln consisted of 31%, with 23% coming from the cooling air and the remainder from the clinker's energy. After transferring the clinker energy to the cooling air, it amounts to 8%. It was observed that by improving the structure of the cyclones and adding additional cyclones, more hot gas drawn from the rotary kiln to the preheating cyclones could increase the amount of raw material entering the kiln.

Adeniran et al. [38] conducted a study to improve a cement production facility in Nigeria. Through process analysis, exergy analysis, and predicting air pollutant emissions, they calculated the exergy efficiency to be 27.35%. They found that the exergetic efficiency of the kiln system could be further improved not only by preheating the limestone but also by preheating the primary air and natural gas.

Zandieh et al. [39] conducted a study comparing alternative fuels and coal. The alternative fuels used in the study are shown in Table 2.

Table 2. Composition of alternative fuels [56].

Element	%RDF	%TDF
C	60	70
H	10	7
O	25	10
S	1	1.5
N	0.1	0.5

Eq. 15 in the study illustrates the method used to calculate the mass flow rate of the alternative fuels.

$$\dot{n}_{coal} HHV_{coal} = \dot{n}_{AF} HHV_{AF} \quad (15)$$

The study utilized mass balance and energy balance analyses. It observed that replacing fossil fuels with alternative fuels reduces CO_2 emissions from the kiln. The study provided information about the advantages and disadvantages of using alternative fuels. It observed lower heat loss in alternative fuels and noted that the use of alternative fuels in cement kilns not only offers environmental and economic benefits but also advantages in terms of energy and exergy efficiency.

Additionally, Figure 14 presents the CO_2 emission graph of alternative fuels. It is observed that RDF alternative fuel has lower CO_2 emissions due to its low percentage of carbon in its composition. RDF (Refuse Derived Fuel) is a processed form of municipal solid waste used as a fuel. TDF (Tire Derived Fuel) consists of shredded scrap tires. Both are considered alternative fuels with varying impacts on emissions and combustion efficiency.

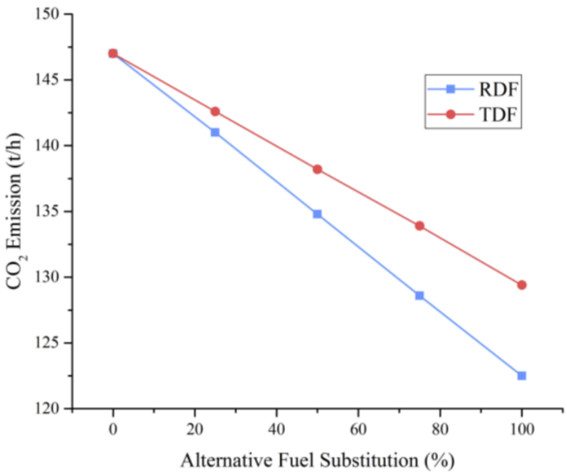

Figure 14. CO_2 emissions of alternative fuels [39].

In the study conducted by Emyat B. G., a case study was conducted to determine the energy saving and heat recovery potential in a 2,000 tons/day capacity cement factory in Ethiopia. They proposed the installation of an auxiliary circuit such as WHRSG (Waste Heat Recovery Steam Generator). It was suggested that a secondary shell system should be applied to minimize heat loss from the kiln shell. With the use of these systems, approximately 3.5 MW of energy savings are achieved from the kiln surface, which corresponds to the recovery of about 9% of the total input energy. By analyzing the energy usage in the factory, potential improvements in energy efficiency were identified. In conclusion, the study highlights the significant energy saving potential of heat recovery in cement kilns and the availability of various recovery options.

Table 3. Rotary kiln energy balance [41].

Inlet		**Outlet**	
Components	**Flow (kj/h)**	**Components**	**Flow (kj/h)**
Kiln feed	364,584,546.3	Exhaust gas	150,527,377.0
Secondary air	119,761,060.3	Clinker	694,572,383.2
Primary air	48,758.5	Heat loss	375,644,605.4
Coal	1,101,593.1		
Clincer reaction	417,030,673.3		
Sensible heat of coal	318,217,734.0		
Total	**1,220,744,365.6**	**Total**	**1,220,744,365.6**

The study conducted by Nasution et al., focuses on the examination of a rotary kiln unit in the cement industry based on energy and exergy analyses. In the article, thermodynamic analyses were conducted to improve the energy efficiency of the coal-fired rotary kiln in the cement factory. According to the analysis results, the energy efficiency was determined as 69.20%, the exergy efficiency as 50.48%, and irreversibility as 49.52%.

In the study conducted by Nasution et al., the values of the energy and exergy balance of the rotary kiln according to the input and output parameters are shown in Table 3 and Table 4.

Table 4. Rotary kiln exergy balance [41].

Inlet		**Outlet**	
Components	**Flow (kj/h)**	**Components**	**Flow (kj/h)**
Kiln feed	746,835,463.7	Exhaust gas	114,196,099.9
Secondary air	73,862,852.0	Clinker	602,651,832.1
Primary air	467,300.0	Destructed Exergy	703,086,805.1
Coal	598,769,121.3		
Total	**1,419,934,737.1**	**Total**	**1,419,934,737.1**

They found that the largest energy loss was due to the high temperature of the kiln gas outlet, and the largest losses were from process (internal) exergy losses.

Atmaca et al. [42] examined the parameters affecting the energy consumption of a rotary kiln in the cement industry. After summarizing the working principle of rotary kilns and the cement production process, they determined the effects of factors such as the characteristics of the kiln feed material, gas temperature inside the kiln, combustion air volume, rotary kiln speed, and kiln insulation on energy consumption. They separately calculated the heat transfer from the rotary kiln to the atmosphere due to the temperature difference between the inner surface of the kiln and the ambient air temperature. Heat transfer from the kiln occurs through conduction, convection, and radiation. Significant amount of heat is transferred from the surface to the atmosphere, considered as waste heat. Preserving this heat will increase the thermal efficiency of the rotary kiln. The energy consumed during clinker formation is calculated to obtain the overall energy balance of the system.
The components of the rotary kiln are shown in Figure 15.

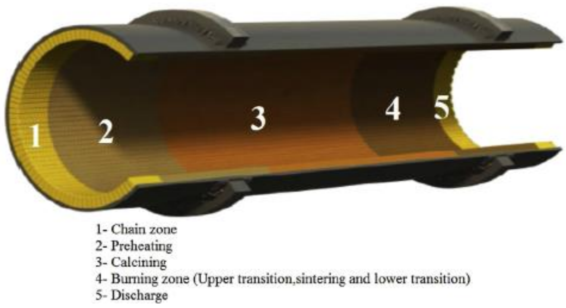

Figure 15. Rotary kiln zones [42].

$$R_{conv,1} = \frac{1}{2\pi r_4 L_1 h_1} \tag{16}$$

$$R_{cond,1} = \frac{1}{2\pi L_1 k_1} ln\frac{r_3}{r_4} \tag{17}$$

$$R_{cond,2} = \frac{1}{2\pi L_1 k_2} ln\frac{r_2}{r_3} \tag{18}$$

$$R_{cond,3} = \frac{1}{2\pi L_1 k_3} ln\frac{r_1}{r_2} \tag{19}$$

$$R_{conv,2} = \frac{1}{2\pi r_1 L_1 h_2} \tag{20}$$

$$R_{rad} = \frac{1}{2\pi r_1 L_1 h_{rad}} \tag{21}$$

Refractory arrangement and anzast layer in rotary kiln is shown in Figure 16.

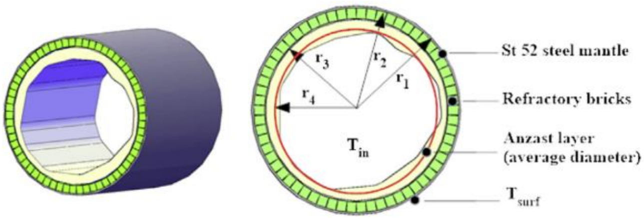

Figure 16. Refractory arrangement and anzast layer in rotary kiln [42].

The article includes suggestions such as optimizing the volume of combustion air, adjusting the speed and temperature of the kiln, controlling material properties, and improving kiln insulation. According to the analysis results, they calculated the energy efficiency as 55.8% and the exergy efficiency as 38.7%. They presented the results in Sankey and Grassman diagrams.

Sankey diagrams are used to understand where and how energy losses occur. This diagram helps determine where improvements can be made to increase energy efficiency. This diagram is a Sankey diagram showing the energy flow in a rotary kiln. It visualizes the energy transfers between energy inputs (e.g., fuel and air) and outputs (e.g., clinker and waste gases).

Grassmann diagrams are used to understand where and how exergy losses occur. This diagram helps determine where improvements can be made to increase exergy efficiency. This diagram is a Grassmann diagram showing the exergy flow in a rotary kiln. It visualizes the relationship between exergy inputs and outputs and exergy losses.

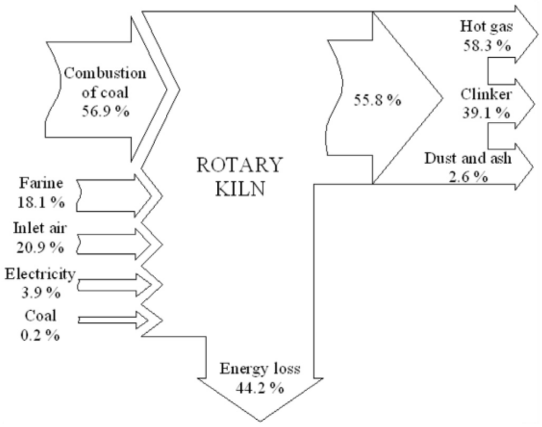

Figure 17. Energy diagram of rotary kiln (Sankey).

In their study, Ma, Shao and Cui examined the energy consumption and thermodynamic efficiency of a typical cement production system based on experimental and simulation studies. The article provides a detailed explanation of the studies conducted on the energy consumption and thermodynamic efficiency of a 5,000 ton/day capacity rotary kiln in a cement factory. While experimental studies were conducted by making measurements in a real cement factory, simulation studies were carried out using a cement production simulation program. Various parameters such as energy consumption in the cement production process, thermal efficiencies, energy, and exergy analyses were calculated and analyzed based on the analysis results.

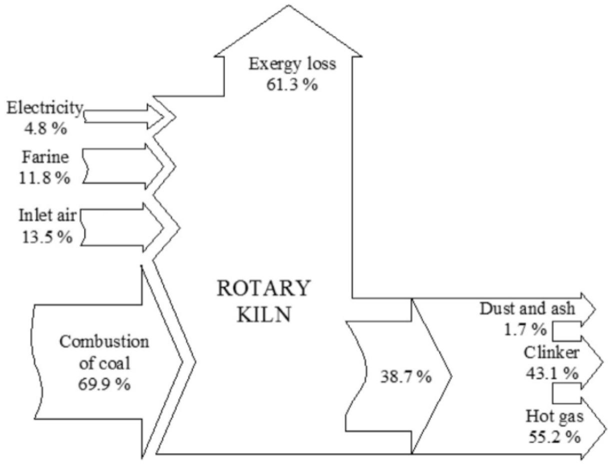

Figure 18. Rotary kiln exergy diagram (Grassman).

In their study, Song et al., conducted an exergy analysis of the main processes in the cement production chain (grinding, calcination, clinkering, and cooling), and determined the total exergy losses of the chain.

In exergy calculations,

The exergy produced by electrical energy, Ee, is expressed as follows:

$$E_e = W \tag{22}$$

The exergy of heat is equal to the maximum thermodynamic work transferred between the system and the surroundings.

*In this study, temperature is assumed to be constant.

$$E_f = Q \times \left(1 - \frac{T_0}{T}\right) \tag{23}$$

Here, Q represents the amount of heat transferred from the high-temperature heat source to the surroundings (unit: kJ).

The sensible heat exergy is calculated as follows:

$$E_h = MxC \times \left[(T - T_0) - T_0 ln\frac{T}{T_0}\right] \tag{24}$$

The chemical exergy Erc of raw materials in the cement production process is given as follows:

$$E_{rc} = m\,[(H - H_0) - T_0(S - S_0)] \tag{25}$$

The article highlights that significant exergy losses occur in the main processes of the cement production chain, particularly during the calcination and clinkerization stages, due to the high temperatures involved and the lack of recovery of by-products. It suggests various recommendations to reduce exergy losses in the cement production chain, such as the use of recovery technologies for the calcination process.

In their study, Atmaca and Yumrutaş [42] have presented a methodology for thermodynamic and exergoeconomic analyses of a cement plant. They first describe the cement production process in detail and develop mathematical models for thermodynamic analysis along with the creation of energy and entropy balance tables.

Additionally, they have drawn the diagram of a real cement plant in their study. It is shown in Figure 19.

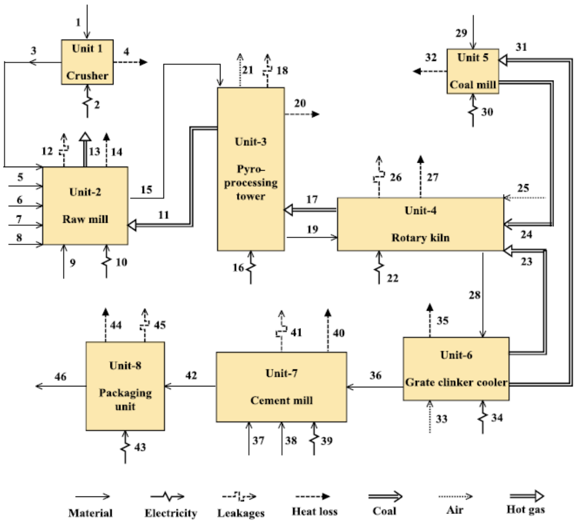

Figure 19. Diagram of a real cement factory [45].

In the exergoeconomic analysis, economic parameters such as cost and price are taken into account in addition to the thermodynamic analysis model to determine the exergoeconomic efficiency of the cement plant. The study also presents energy and exergy balance tables for the cement plant.

In their study, [11] have applied thermodynamic and exergoeconomic analysis to a cement factory. The article covers thermodynamic and exergoeconomic analyses of all components of the cement factory, including grinding, calcination, grinding auxiliary systems, etc. Economic data are obtained from actual supplier quotations during the calculation of the plant's cost ratios. To obtain more accurate results than thermoeconomic analysis, they have determined the cost distributions of subsystems by considering the main units. Energy loss rates for the units of the plant are shown in Figure 20.

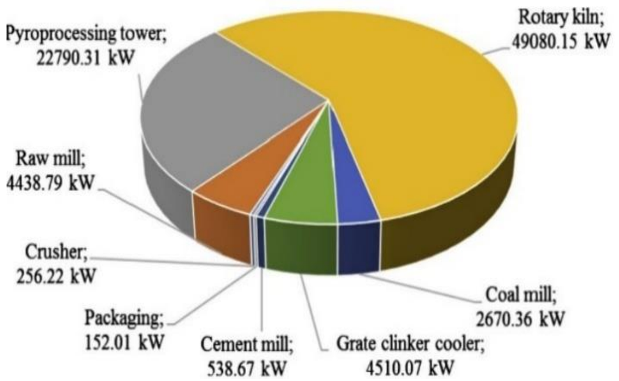

Figure 20. Energy loss rate in the components of the facility [11].

Exergoeconomic analysis consists of both economic and exergy analyses. Through thermoeconomic analysis, the cost ratio of exergy consumption and exergoeconomic performance parameters (i.e., relative cost difference and exergoeconomic factors) of a system and its components are determined.

The total cost percentages of plant components are shown in Figure 21.

Taweel et al. [46] conducted a study focusing on the thermodynamic and exergy characteristics of clinker coolers, and they calculated the energy and exergy efficiencies. The results obtained in the article indicate that the energy consumption of clinker coolers is high and various measures can be taken to increase efficiency. These measures include installing heat recovery systems in clinker coolers, improving insulation, reducing air flow rates, and minimizing water consumption.

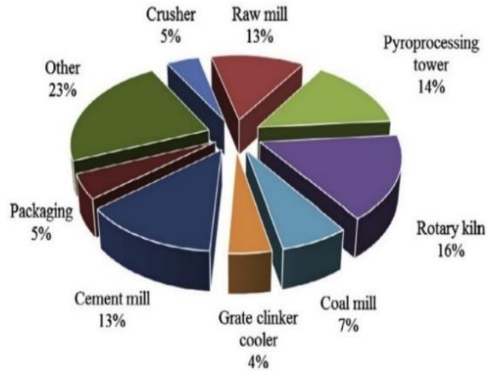

Figure 21. Total cost percentages of the plant's components [11].

Kandilci et al. [47] conducted a study on energy efficiency in the cement sector, where they performed energy and exergy analyses. They used actual data from a 12-month period for their analysis. Recognizing that analyzing the entire factory as a single system could be misleading, they evaluated each system separately. According to the study's findings, the energy efficiency of the raw mill was determined to be 74%, with an exergy efficiency of 12%. The coal mill exhibited a high energy efficiency of 97%, but its exergy efficiency was found to be at a normal level. As for the cement mill, while its energy efficiency was at a normal level, its exergy efficiency was calculated to be 87%.

The study conducted by Engin & Arı, [48] focuses on the energy audit analysis of a dry rotary kiln system operating in a cement factory in Turkey. The schematic representation of the rotary kiln system considered for energy audit is depicted in Figure 23.

The control volume, various streams, and components for the furnace system are shown in Figure 22.

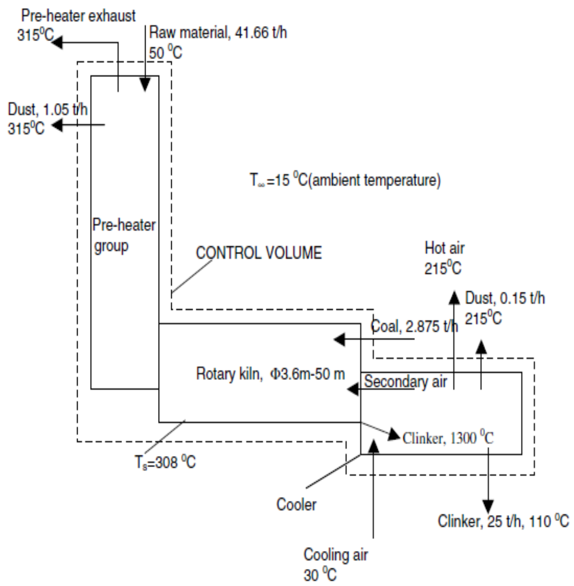

Figure 22. Control volume, various flows and components for the furnace system [48].

The study investigated the energy losses in the rotary kiln system, revealing that approximately 40% of the total input energy is lost through hot waste gases, cooler exhausts, and the kiln shell. The results of the research indicate that approximately 15.6% of the total input energy could be recovered.

Mokrzycki et al. [49] discuss the increasing use of alternative fuels in the cement industry as an alternative to traditional fuels such as coal, oil, and natural gas. The article highlights that the increased use of alternative fuels in cement production can lead to more sustainable production. Additionally, the impact of alternative fuels on the quality of cement, production processes, and costs in cement production has been examined.

Arı [50] conducted a study on the energy and exergy evaluations of a 297-ton/h capacity cement rotary kiln system. According to the analysis results, the energy efficiency of the rotary kiln system was determined to be 54.9%, while the exergy efficiency was found to be 28.1%.

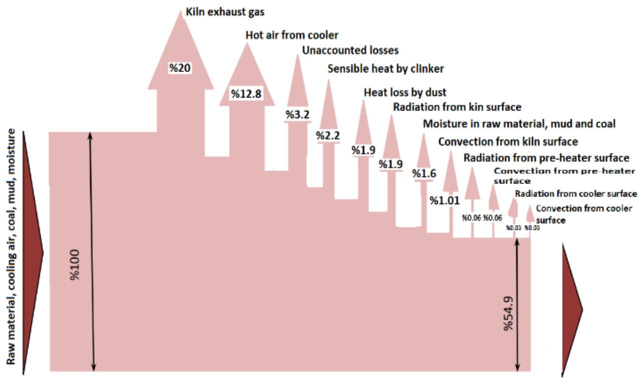

Figure 23. Sankey diagram of energy balance [50].

In their study, Utlu et al. [51] conducted an energy and exergy analysis of the grinding system. The energy and exergy efficiency of the grinding system were determined to evaluate its performance. Through thermodynamic first and second law analyses, the energy efficiency of the grinding system was found to be 84.3%, while the exergy efficiency was determined to be 25.2%. Based on the results of the study, various strategies were proposed to enhance energy and exergy efficiency, such as reducing air intake, improving insulation of the grinding system, and using suitable grinding rods for the grinding material.

In their study, Yin et al. [52] focused on the design and economic analysis of heat exchangers for waste heat recovery in rotary kilns used in cement production. The research investigated the efficiency and economic returns of waste heat recovery through simulations and economic analyses using different design parameters. The results of the study indicated that efficient utilization of waste heat from rotary kilns could lead to energy savings and reduced environmental impact by identifying appropriate design parameters.

Nandhini et al. [54] investigated the waste heat recovery systems of a cement factory with a production capacity of 6000 tons/hour. In the study, energy and exergy efficiency were calculated as 59.6% and 61.9%, respectively. It was also stated that waste heat recovery in cement production provided energy savings and in terms of reducing greenhouse gas emissions, the lowest levels were reached as 17.9 and 16.1 on a ton/kW basis.

E. Bani-Hani et al. [55] evaluate the effects of alternative fuel usage by examining the energy and exergy efficiency of the regenerative Brayton cycle used in cement production. The study compares the total emissions and energy consumption rates leveled at 120.8 tons/kW. It also shows how the system can optimize combined heat and power production with oxyfuel combustion.

In today's cement industry, continuous advancements in research regarding energy efficiency and sustainable production are being made. Through our literature review, we observed a focus on traditional methods in exergy and energy analysis studies of the cement plant rotary kiln process. However, we found a gap in studies utilizing artificial neural networks and the Taguchi method for analysis. Although Artificial Neural Networks (ANN) and the Taguchi method show promise, it is considered that recently developed and emerging approaches such as Particle Swarm Optimization (PSO), Simulated Annealing (SA), and Response Surface Methodology (RSM) can also be employed to evaluate their effectiveness in complex and multivariable systems like rotary kilns.

In this context, the proposed study offers an innovative approach to enhancing energy efficiency in cement production by integrating artificial neural networks and the Taguchi method. The absence of such original methodology in the existing literature suggests that the proposed study would fill this gap, contributing significantly to industrial applications and adding a new dimension to research in the sector.

3. Energy and Exergy Analysis Equations

Under this heading, various formulas from different literature sources discussing energy and exergy analyses conducted on the cement plant rotary kiln process have been examined. The first and second law equations of thermodynamics have been demonstrated. Each formula has been referenced to its respective literature source.

The compilation of these analyses highlights the importance of energy efficiency and exergy analyses in the cement industry, demonstrating the diversity of relevant literature sources and the various dimensions of the analyses. Mass balance analyses conducted for the cement plant rotary kiln process are important tools for evaluating material flows within the process and understanding process performance. Various literature sources propose different mass balance equations to describe material flows in cement production processes. These equations typically define the input of raw materials and the output of clinker and by-products. Mass balance equations according to different literature sources are shown in Table 5.

Mass balance equations are essential for evaluating material flows in cement production. This table allows readers to compare different approaches to mass balance calculations and understand how they are applied in the context of cement rotary kilns.

Mass balance is a fundamental principle in process engineering and these equations are used to minimize material losses and increase process efficiency.

The conservation of energy equations are fundamental tools used to analyze energy transfers in the cement plant rotary kiln process and maintain the energy balance of the process. Various literature sources propose different equations based on the principle of energy conservation. These equations form an important basis for energy efficiency analyses and are used to assess process performance. The equations obtained from different literature sources provide information to optimize energy consumption in cement production processes and reduce environmental impacts. Table 6 shows the conservation of energy equations according to various literature sources.

Table 5. Mass balance equations according to various literature sources.

Researcher	Mass Balance Equation
Gürtürk et al. [24], Altınkaynak et al. [25], Altınkaynak et al. [37], Emyat B. G. et al. [53], Zandieh A. et al..[39], Nasution S. et al [41], Atmaca et al. [42], Taweel et al. [46], Arı [50], Utlu et al. [51],	$\sum \dot{m}_{in} = \sum \dot{m}_{out}$
Gürtürk [28]	$\frac{m_{cv}}{dt} = \sum_{in} \dot{m}_{in} - \sum_{out} \dot{m}_{out}$
Çamdalı et al. [32]	$\sum(\dot{m}_{farine} + \dot{m}_{coal} + \dot{m}_{air}) = \sum(\dot{m}_{clinker} + \dot{m}_{dust} + \dot{m}_{s-gases})$

Energy conservation equations are critical for understanding how energy is used and lost in cement production. This table provides a reference for readers to see how different studies have approached energy conservation in rotary kilns.

Energy conservation is one of the fundamental principles of thermodynamics and is used to analyze energy transfers and losses.

Table 6. Energy conservation equations according to various literature sources.

Researcher	Energy Conservation Equation
Gürtürk et al. [24]	$-\dot{E}_k + \dot{E}_{yh} + \dot{E}_{DG} + \dot{E}_G + \dot{E}_{bgg} + \dot{E}_n - \dot{E}_{bg} - \dot{E}_{gp} = 0$ $0 = \dot{E}_k - \dot{W}_{kh} + \sum_{in} \dot{m}\left(h + \frac{1}{2}V^2 + gz\right) - \sum_{out} \dot{m}\left(h + \frac{1}{2}V^2 + gz\right)$
Gürtürk et al. [24] Zandieh et al. [39], Nasution et al. [41], Atmaca et al. [42], Taweel et al. [46], Arı [50], Utlu et al. [51], Altınkaynak et al. [25]	$\sum \dot{E}_{in} = \sum \dot{E}_{out}$ $\sum \dot{m}_{in}h_{in} = \sum \dot{m}_{out}h_{out}$ $\dot{Q}_{net,giren} - \dot{W}_{net,çıkan} = \sum_{çıkan} \dot{m}\, h_{çıkan} - \sum_{giren} \dot{m}\, h_{giren}$ $\dot{Q} - \dot{W} = \sum \dot{m}_ç \left(h + \frac{V^2}{2} + gz\right) - \sum \dot{m}_g \left(h + \frac{V^2}{2} + gz\right)$
Çamdalı et al. [32]	$Q_{cv} + \sum_{in} m_{in}(h_f^0 + \Delta h + \frac{V_{in}^2}{2} + g_G z_{in}) = W_{cv} + \sum_{out} m_{out}\left(h_f^0 + \Delta h + \frac{V_{out}^2}{2} + g_G z_{out}\right) + Q_L$
Uğur et al. [36]	$\Delta E_{sistem} = \Delta U + \Delta E_k + \Delta E_p$
Emyat [53]	$\sum \dot{Q}_{in} = \sum \dot{Q}_{out}$ $\dot{Q} = \dot{m}c_p \Delta T$

The first law expresses the principle of conservation of energy and determines how much energy is used within a process or transferred to the environment. Various literature sources propose different formulas to calculate the efficiency of the first law. These formulas are important for analyzing energy transfers in the cement plant rotary kiln process and optimizing energy usage. Table 7 displays the efficiency of the first law according to different literature sources.

Comparing First Law efficiencies from different studies helps identify trends and variations in energy efficiency across different cement production processes. This table provides a benchmark for evaluating the performance of rotary kilns.

First Law efficiency is used to evaluate the effectiveness of energy use and is an important metric for process optimization.

Table 7. Efficiency of the first law according to different literature sources.

Researcher	Efficiency of the First Law
Gürtürk et al. [24] Gürtürk et al. [28] Atmaca et al. [42], Taweel et al. [46],	$\eta_I = \frac{\sum \dot{E}_{out}}{\sum \dot{E}_{in}}$
Söğüt [1], Uğur et al. [36], Utlu et al. [51],	$\eta_I = \frac{\sum m_{out}h_{out}}{\sum m_{in}h_{in}}$
Altınkaynak et al. [25], Madlool et al. [26], Arı [50]	$\eta_I = \frac{obtained\ exergy}{provided\ exergy}$ $\eta_I = \frac{clincer\ formation\ energy}{input\ energy} = 1 - \frac{output\ energy}{input\ energy}$
Çamdalı et al. [32],	$\eta = \left\lvert\frac{\sum m_{out}(h_{T,P})}{\sum m_{in}(h_{T,P})}\right\rvert$
Altınkaynak et al. [37]	$\eta_I = \frac{\sum \dot{E}_{useful}}{\sum \dot{E}_{in}}$

Table 8. Exergy balance according to various literature sources.

Researcher	Exergy Balance
Madlool et al. [26], Nasution et al. [41], Atmaca et al. [42], Atmaca et al. [45]	$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_{system}$ $\sum \dot{E}x_{dest} = \sum\left(1 - \frac{T_0}{T_k}\right)Q_k - W + \sum m_{in}\psi_{in} - \sum m_{out}\psi_{out}$ $\psi = (h - h_0 - T_0(s - s_0)$
Gürtürk et al. [24], Utlu et al. [51], Altınkaynak et al. [25], Uğur et al. [36], Gürtürk et al. [28], Zandieh et al. [39]	$\sum \dot{E}x_{in} - \sum \dot{E}x_{out} = \sum \dot{E}x_d$ $\dot{E}x_Q - \dot{E}x_W = \sum_{out} \dot{m}\mathcal{E} - \sum_{in} \dot{m}\mathcal{E} + T_0 S_{product}$ $\sum \dot{E}x_{in} - \sum \dot{E}x_{out} - \sum \dot{E}x_{loss} = \sum \dot{E}x_d$ $\dot{E}x_{loss} = \dot{Q}_{loss}(1 - \frac{T_0}{T_{surf}})$
Koroneos et al. [30], Çamdalı et al. [32], Adeniran et al. [38]	$E_{product} = E_{in} - E_{losses} - E_{waste}$ $E^{in} - E^{ex} - E^Q - E^L = E^S$

Exergy balance is an approach aimed at analyzing the exergy transfers within a system to determine energy losses in the system. Various literature sources provide different tables and equations for conducting exergy balance analysis of the cement plant rotary kiln process. Table 8 presents exergy balance formulas according to various literature sources.

Exergy balance equations are essential for understanding where and how energy is lost in cement production. This table allows readers to compare different approaches to exergy analysis and their implications for improving energy efficiency.

Exergy analysis is used to determine exergy losses and irreversible energy losses. It also measures the quality of energy and is used to increase the thermodynamic efficiency of processes.

Second Law efficiency is a critical metric for evaluating the thermodynamic performance of cement production processes. This table helps readers understand how different studies have calculated and interpreted Second Law efficiencies.

Second Law efficiency is a critical metric for evaluating the thermodynamic performance of processes and measuring irreversible losses.

Table 9. Efficiency of the second law according to different literature sources.

Researcher	Efficiency of the Second Law
Söğüt [1], Gürtürk et al. [24], Gürtürk et al. [28], Uğur et al. [36], Adeniran et al. [38], Emyat [53], Atmaca et al. [42], Taweel et al. [46], Utlu et al. [51]	$\eta_{II} = \frac{\sum \dot{E}x_{out}}{\sum \dot{E}x_{in}}$
Söğüt [1], Uğur et al. [36]	$\eta_{II} = \frac{\sum \dot{E}x_{out} - \sum Ex_{tr}}{\sum \dot{E}x_{in} - \sum Ex_{tr}}$
Altınkaynak et al. [25], Koroneos et al. [30], Arı [50], Madlool et al. [26]	$\eta_{II} = \frac{obtained\ exergy}{provided\ exergy} = 1 - \frac{exergy\ destruction}{provided\ exergy}$ $\eta_{II} = \frac{clinker\ formation\ exergy}{input\ exergy} = 1 - \frac{output\ exergy + irreversibilty}{input\ exergy}$
Madlool et al. [26]	$\eta_{kiln} = \frac{ex_p - ex_{np}}{ex_f + ex_{ep}}$
Çamdalı et al. [32]	$\psi = \frac{\sum m_{out}\varepsilon_{out}}{\sum m_{in}\varepsilon_{in}} = 1 - \left[\frac{\sum E^L}{\sum m_{in}\varepsilon_{in}}\right]$
Atmaca et al. [45]	$\eta_{II} = \frac{\sum \dot{E}x_{desired\ output}}{\sum \dot{E}x_{used}}$ $\eta_{II} = \frac{Product\ (clincer, cement, etc\ ...)}{Fuel\ (coal, electricity, etc\ ...)}$

Entropy change is a thermodynamic concept that expresses the degree of disorder of a system, and entropy change analysis is used to assess the entropy balance of a system or process. Various literature sources provide different tables and equations to analyze entropy change for the cement plant rotary kiln process. Table 10 shows entropy change formulas according to various literature sources.

Understanding entropy change is crucial for identifying inefficiencies in cement production. This table provides a reference for readers to see how entropy change is calculated and applied in different studies.

Entropy change is used to increase the efficiency of processes and minimize energy losses.

Table 10. Entropy change according to various literature sources.

Researcher	Entropy Change
Gürtürk et al. [24], Adeniran et al. [38], Altınkaynak et al.[25],	$s_2 - s_1 = c_{p,ort} \ln\frac{T_2}{T_1} - R\ ln\frac{P_2}{P_1}$
Atmaca et al. [42], Atmaca et al. [45]	$s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} - Rln\ \frac{v_2}{v_1} = c_{v,ort} ln\frac{T_2}{T_1} + Rln\frac{v_2}{v_1}$ $s_2 - s_1 = \int_1^2 c(T)\frac{dT}{T} - Rln\ \frac{v_2}{v_1} = c_{p,ort} ln\frac{T_2}{T_1} - Rln\frac{P_2}{P_1}$
Gürtürk et al. [28]	$(s_k - s_\infty) = C_{p,k} \ln\left(\frac{T_k}{T_\infty}\right) - R \ln\left(\frac{P_k}{P_\infty}\right)$

Exergoeconomic analysis is a methodology used to evaluate the relationship between thermodynamic efficiency and economic costs. Various literature sources provide different tables and equations to identify and analyze exergoeconomic analysis formulas for the cement plant rotary kiln process. Table 11 presents exergoeconomic analysis equations according to different literature sources.

Exergoeconomic analysis is essential for identifying cost-effective strategies for improving energy efficiency in cement production. This table provides a reference for readers to understand how exergoeconomic principles are applied in the context of rotary kilns.

Exergoeconomic analysis helps determine cost-effective strategies to increase energy efficiency.

Table 11. Exergoeconomic analysis according to different literature sources.

Researcher	Exergoeconomic Analysis
Gürtürk et al. [24],	$\sum_{in} \dot{C} + \dot{C}_k + \dot{Z} = \sum_{out} \dot{C} + \dot{C}_w$
Söğüt [1]	$C_{ex_ç} = \frac{C_{ex_{mç}}}{\mu_U \xi_T} + \frac{Z_p}{\sum \dot{E}x_p}$
Atmaca et al. [45]	$\sum_i (c_i \dot{E}x_i) + c_w \dot{E}x_w + \dot{Z}_k = \sum_e (c_e \dot{E}x_e) + c_q \dot{E}x_q$

4. Results

This study provides a comprehensive review of energy, exergy, and exergoeconomic analyses in cement rotary kilns, highlighting the potential for significant energy savings and sustainability improvements. The findings reveal that exergy efficiencies in cement production units vary between 16% and 67%, with the highest losses occurring in the rotary kiln due to its irreversible nature. Strategies such as waste heat recovery, the use of alternative fuels, and advanced process optimization techniques have been identified as key to improving energy efficiency.

However, several gaps remain in the current literature. The integration of advanced optimization techniques, such as artificial neural networks and the Taguchi method, has not been sufficiently explored in the context of cement production. Future research should focus on the application of these techniques to further enhance energy efficiency and reduce environmental impacts.

Although this review article offers a comprehensive overview of the literature on energy, exergy, and exergoeconomic analyses in the cement industry thereby providing a valuable knowledge base it would benefit significantly from a more in-depth comparison of the methods and results examined. In this context, a structured comparison of the analytical techniques, assumptions, system boundaries, and performance indicators employed in different studies would not only allow readers to understand the existing body of work, but also provide a critical perspective on methodological consistency, practical applicability, and the reliability of results. As a result, the article would transcend its role as a summary and take on a guiding function, offering researchers and practitioners concrete insights into which approaches yield more efficient and sustainable outcomes.

In conclusion, this study not only consolidates existing knowledge but also provides a roadmap for future research and industrial applications. By addressing the identified gaps, the cement industry can move towards more sustainable and energy-efficient production processes.

Future Scope: Future research should focus on the following areas to further enhance energy efficiency and sustainability in cement production:

Integration of artificial neural networks (ANNs) and the Taguchi method for optimizing rotary kiln operations.

Development of advanced waste heat recovery systems to maximize energy utilization.

Exploration of new alternative fuels and their impact on clinker quality and emissions.

Implementation of carbon capture and storage (CCS) technologies to reduce greenhouse gas emissions.

Life cycle assessment (LCA) studies to evaluate the environmental impacts of different cement production processes.

Limitations of Study: This study has several limitations that should be acknowledged:

The review is primarily based on existing literature, and the findings are limited by the quality and scope of the studies reviewed.

The proposed integration of advanced optimization techniques, such as ANNs and the Taguchi method, is theoretical and requires empirical validation through case studies.

The economic feasibility of implementing some of the proposed strategies, such as carbon capture technologies, has not been thoroughly explored.

The study focuses mainly on energy and exergy analyses, and other environmental impacts, such as water usage and raw material depletion, are not address

Opportunities for Improving Energy Consumption Models: Our research findings indicate numerous opportunities for enhancing energy consumption models in cement production. Specifically, strategies have been identified to minimize or recover energy losses at specific process steps. Practical solutions such as recovering waste heat in the preheating process or utilizing alternative fuels more effectively can be recommended.

Environmental Impacts of Recommended Strategies to Increase Energy Efficiency: Our research findings indicate that strategies proposed to enhance energy efficiency in cement production have the potential to improve environmental sustainability. Specifically, it has been determined that reduced energy consumption and the use of more efficient processes can lead to reductions in greenhouse gas emissions and a decrease in environmental footprint.

Guidance for Future Research and Applications: Our study provides a comprehensive roadmap for future research and applications in the cement industry based on the in-depth insights gained. Specifically, there is a need for more detailed examination and development of new methods for optimizing energy flows in the rotary kiln process. Additionally, a more comprehensive evaluation of the relationship between energy and economics could help make cement production operations more economically viable and sustainable.

Recommendations for Process Optimization: Our study provides concrete recommendations for improving the energy efficiency of the rotary kiln process in cement production. Among the recommended strategies for process optimization are more efficient fuel usage, waste heat recovery, development of process integration, and improvement of process control systems. Implementing these recommendations can help the cement industry reduce energy consumption and optimize production costs.

The Role of Technological Developments: Our study highlights the potential impact of technological innovations on energy efficiency in the cement production process. Specifically, developments such as innovative fuel options, new technologies for process integration, and efficient energy recovery systems have been identified to lead to significant improvements in industrial operations. Future research should further investigate how such technological developments can be integrated into the cement production process and enhance energy efficiency.

In recent years, the rapid development of artificial intelligence (AI) technologies has brought about significant transformations in the optimization and management of industrial facilities. Cement production plants have greatly benefited from these technologies as well. AI-enabled automation systems enable processes to be managed more intelligently and efficiently. Specifically in cement production, AI applications are used for better monitoring, analysis, and optimization of processes. Insights obtained from analyzing large datasets become a valuable resource for enhancing plant performance and optimizing energy efficiency.

AI-powered systems are used in cement plants to monitor energy consumption, adjust process parameters, and provide automatic optimization. Additionally, AI-based predictive models can identify potential issues at specific stages of cement production, allowing for preemptive maintenance optimization and thereby increasing operational efficiency of the facility. The adoption of these technologies can reduce labor costs, minimize operational risks, and enhance the stability of the facility.

Looking ahead, the use and development of AI and automation technologies in the cement industry are expected to become more widespread. With the implementation of these technologies, plant energy efficiency will improve, environmental impacts will be minimized, and production processes will become more sustainable. However, it's crucial to address technical, operational, and security issues carefully during the implementation and integration of AI-enabled automation.

In conclusion, AI-enabled automation systems can be a critical tool for improving operational efficiency and optimizing energy consumption in cement plants. With effective utilization of these technologies, industrial facilities can become more competitive and better achieve sustainable production goals.

Cost-Effectiveness Analysis: Our study's findings provide valuable insights into the cost-effectiveness of strategies proposed to improve energy efficiency. Through exergoeconomic analysis and cost-effectiveness calculations, information has been gathered about the feasibility and payback periods of specific strategies. This information can guide industry professionals and decision-makers in determining energy management strategies for cement production.

Sustainability and Social Impact: The results of our study emphasize that increasing energy efficiency in the cement industry can have positive impacts not only on the industry itself but also on the environment and society. Reduced energy consumption, lower emissions, and more efficient use of resources are important steps toward a sustainable future. Therefore, efforts to improve energy efficiency in the cement industry should consider the social and environmental dimensions of these initiatives.

The findings of this study provide an important foundation for guiding future research on energy management and sustainability in the cement industry. Future studies should evaluate the practical implementation of the strategies we propose and examine how innovative technologies can be integrated to enhance energy efficiency in the cement production process. Additionally, there should be more emphasis on approaches focused on societal acceptance and collaboration, which can enhance the success of energy efficiency projects in the industry and accelerate industrial transformation processes.

Ultimately, improving energy efficiency in the cement industry can contribute significantly to a sustainable future, providing important benefits both economically and environmentally.

Nomenclature

A	surface area (m^2)
C	flow velocity (m/s)
cp	specific heat capacity at constant pressure (kJ/kg K)
E	exergy (kJ), energy (kJ)
E_{ex}	exit exergy (kJ)
E_{in}	inlet exergy (kJ)
EL	lost exergy due to irreversibilities (kJ)
EO	outlet exergy (kJ)
EQ	exergy of heat transfer (kJ)
ES	exergy of a system (kJ)
EW	exergy of work transfer (kJ)
g	specific Gibbs function (kJ/kg)
G	gravitational acceleration (m/s2)
h	specific enthalpy (kJ/kg)
h	convective heat transfer coefficient (kJ/hm2 K)
I	irreversibility (kJ)
k	thermal conductivity (kJ/hmK)
l	length of RB (m)
m	mass (kg)
P	pressure (kPa)
Q	heat transfer (kJ)
Q_L	heat loss (kJ)
r	radius (m)
RB	rotary burner
S	entropy (kJ/K)
s	specific entropy (kJ/kgK)
T	temperature (K)
T_{in}	inner temperature of RB (K)
T_{sur}	surface temperature of RB (K)
V	volume (m3), velocity (m/s)
W	work (kJ)
z_0	height of flow (m)
μ	chemical potential (kJ/kmol)
ŋ	energy efficiency (%)
ψ	exergy efficiency (%)
Ɛ	specific exergy (kJ/kg)

CEMBUREAU - The European Cement Association
ASME - American Society of Mechanical Engineers
RDF - Refuse Derived Fuel
TDF - Tire Derived Fuel

References

[1] M. Z. Söğüt, Z. Oktay, and H. Karakoç, "Exergoeconomic Optimization of Rotary Kiln Process in the Cement Sector," Ph.D. dissertation, Dept. Mech. Eng., Balıkesir University, Balıkesir, Turkey, 2009.

[2] T. Çimento, *Turkish Cement Sector in 2022*. Ankara, Turkey: Turkish Cement Manufacturers' Association, 2022.

[3] T.E. Association, Cembureau, 2023. [Online]. Available: http://www.cembureau.be/about-cement/key-facts-figures. (Accessed: Aug. 15, 2023).

[4] K. Volkart, C. Boulet, and C. Bauer, "Life cycle assessment of carbon capture and storage in power," *Int. J. Greenhouse Gas Control*, vol. 16, pp. 91–106, Aug. 2013, doi: 10.1016/j.ijggc.2013.03.003.

[5] Z. Utlu and A. Hepbaşlı, "Energetic and exergetic assessment of the industrial sector at varying dead (reference) state temperatures: A review with an illustrative example," *Renew. Sustain. Energy Rev.*, vol. 12, no.5, pp. 1277–1301, Jun. 2008, doi: 10.1016/j.rser.2007.01.001.

[6] M. A. Rosen and İ. Dinçer, "Effect of varying dead-state properties on energy and exergy analyses of thermal systems," *Int. J. Therm. Sci.*, vol. 43, no. 2, pp. 121–133, Feb. 2004, doi: 10.1016/j.ijthermalsci.2003.05.004.

[7] K. T. Kaddatz, M. G. Rasul, and A. Rahman, "Alternative fuels for use in cement kilns: process impact modelling," *Procedia Engineering*, vol. 56, pp. 413–420, 2013, doi: 10.1016/j.proeng.2013.03.141.

[8] R. Saidur, M. S. Hossain, M. R. Islam, H. Fayaz, and H. A. Mohammed, "A review on kiln system modeling," *Renew. Sustain. Energy Rev.*, vol. 15, no. 5, pp. 2487–2500, Jun. 2011, doi: 10.1016/j.rser.2011.01.020.

[9] J. Ziatabari, A. Fatehi, and M. T. H. Beheshti, "Cement Rotary Kiln Control: A Supervised Adaptive Model Predictive Approach," in *2008 Annu. IEEE India Conf.*, Kanpur, India, Dec. 2008, pp. 371–376, doi: 10.1109/INDCON.2008.4768752.

[10] R. Kajaste and M. Hurme, "Cement industry greenhouse gas emissions – management options and abatement cost," *J. Cleaner Prod.*, vol. 112, pp. 4041–4052, Jan. 2016, doi: 10.1016/j.jclepro.2015.07.055.

[11] A. Atmaca and R. Yumrutaş, "Thermodynamic and exergoeconomic analysis of a cement plant: Part II – Application," *Energy Conversion and Management*, vol. 79, pp. 799–808, Mar. 2014, doi: 10.1016/j.enconman.2013.11.054.

[12] A. Hepbasli, "Low exergy (LowEx) heating and cooling systems for sustainable buildings and societies," *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 73–104, Jan. 2012, doi: 10.1016/j.rser.2011.07.138.

[13] Z. Rant, "Exergy and anergy," *Wissenschaftliche Zeitschrift der Technischen Universität Dresden*, vol. 13, no. 4, pp. 1145–1149, 1964.

[14] J. Szargut, "International progress in second law analysis," *Energy*, vol. 5, no. 8–9, pp. 709–718, Aug. 1980, doi: 10.1016/0360-5442(80)90090-0.

[15] J. Szargut, D. R. Morris, and F. R. Steward, "Exergy analysis of thermal, chemical and metallurgical processes," 1st ed. New York, NY, USA: Hemisphere Publishing, 1988.

[16] T.J. Kotas, “The exergy method of thermal plant analysis,” London, UK: Butterworth-Heinemann, 1985.

[17] M. Shukuya, “Energy, entropy, exergy and space heating systems,” *in proc. 3rd Int. Conf.*, vol. 1. Budapest, Hungary: Healthy Buildings, 1994, pp. 369–374.

[18] P. Sakulpipatsin, “Exergy efficient building design”, Ph.D. dissertation, Faculty of Architecture, Delft University of Technology, Delft, The Netherlands, Apr. 2008.

[19] A. Bejan, *Advanced engineering thermodynamics*, 2nd ed. New York, NY, USA: Wiley, 1997.

[20] L. Connelly and C. P. Koshland, “Exergy and industrial ecology. Part 2: A non-dimensional analysis of means to reduce resource depletion,” *Exergy, Int. J.*, vol. 1, no. 4, pp. 234–255, Jan. 2001, doi: 10.1016/S1164-0235(01)00033-4.

[21] J. Honerkamp, *Statistical Physics: An Advanced Approach with Applications*, 3rd ed. Berlin, Heidelberg, Germany: Springer, 2012.

[22] G. Tsatsaronis, “Definitions and nomenclature in exergy analysis and exergoeconomics,” *Energy*, vol. 32, no. 4, pp. 249–253, Apr. 2007, doi: 10.1016/j.energy.2006.07.002.

[23] Y. A. Çengel and M. A. Boles, Thermodynamics: An Engineering Approach, *5th ed.* McGraw-Hill, 2015.

[24] M. Gürtürk and H. F. Öztop, “Performance Evaluation of a Gypsum Production Plant by Energy, Exergy and Exergoeconomic Analysis Methods,” Ph.D. dissertation, Fırat University, Elazığ, Turkey, 2015.

[25] M. Altınkaynak, A. Kabul, and Ö. Kızılkan, “Thermodynamic Analysis of Rotary Kiln Used in Cement Factories,” M.S. thesis, Süleyman Demirel University, Isparta, Turkey, 2012.

[26] N. A. Madlool, R. Saidur, N. A. Rahim, M. R. Islam, and M. S. Hossian, “An exergy analysis for cement industries: An overview,” *Renewable and Sustainable Energy Reviews*, vol. 16, no. 1, pp. 921–932, Jan. 2012, doi: 10.1016/j.rser.2011.09.013.

[27] M. G. Rasul, W. Widianto, and B. Mohanty, “Assessment of the thermal performance and energy conservation opportunities of a cement industry in Indonesia,” *Appl. Therm. Eng.*, vol. 25, no. 17-18, pp. 2950–2965, Dec. 2005, doi: 10.1016/j.applthermaleng.2005.03.003.

[28] M. Gürtürk and H. F. Öztop, “Energy and exergy analysis of a rotary kiln used for plaster production,” *Appl. Therm. Eng.*, vol. 67, no. 1-2, pp. 554–565, Jun. 2014, doi: 10.1016/j.applthermaleng.2014.03.025.

[29] K. S. Mujumdar, “Modeling of Rotary Cement Kilns,” Ph.D. dissertation, Indian Institute of. Technology, Bombay, Mumbai, India, 2008.

[30] C. Koroneos, G. Roumbas, and N. Moussiopoulos, “Exergy analysis of cement production,” *Int. J. Exergy*, vol. 2, no. 1, pp. 55, 2005, doi: 10.1504/IJEX.2005.006433.

[31] N. A. Madlool, “Assessment of waste preheater gas and dust bypass systems: Al-Muthanna cement plant case study,” *Case Studies in Thermal Engineering*, vol. 8, pp. 330–336, Sep. 2016, doi: 10.1016/j.csite.2016.09.003.

[32] Ü. Çamdalı, A. Erişen, and F. Çelen, “Energy and exergy analyses in a rotary burner with pre-calcinations in cement production,” *Energy Convers. Manag.*, vol. 45, no. 18–19, pp. 3017-3031, Nov. 2004, doi: 10.1016/j.enconman.2003.12.002.

[33] L. M. Farag, “Energy and Exergy Analyses of Egyptian Cement Kiln Plant with Complete Kiln Gas Diversion through by Pass,” *Int. J. Adv. Appl. Sci.*, vol. 1, no. 1, pp. 35–44, Mar. 2012, https://doi.org/10.11591/ijaas.v1i1.757.

[34] C. Sheinbaum and L. Ozawa, “Energy use and CO2 emissions for Mexico’s cement industry,” *Energy*, vol. 23, no. 9, pp. 725–732, Sep. 1998, doi: 10.1016/S0360-5442(98)00022-X.

[35] F. N. Osuolale and O. M. Osuolale, “Thermodynamic Analysis of Cement Production Process Plant in Nigeria,” *Int. J. Sci. Eng. Res.*, vol. 7, no. 9, pp. 820–825, Sept. 2016.

[36] O. Uğur, H. Yamık, and E. Açıkkalp, “Application of Energy and Exergy Analyses on a Rotary Kiln Process in a Cement Plant with Preheater and Calciner,” M.S. thesis, Bilecik Şeyh Edebali University, Bilecik, Turkey, 2018.

[37] M. Altınkaynak, A. Kabul, and Ö. Kızılkan, “Energy Analysis of a Rotary Kiln Process in a Cement Factory,” *SDU Int. Technol. Sci.*, vol. 6, no. 1, pp. 1–12, Apr. 2014.

[38] J. A. Adeniran, R. O. Yusuf, A. S. Aremu, and T. M. Aareola, “Exergetic analysis and pollutants emission from a rotary kiln system in a major cement manufacturing plant,” *Energy & Environment*, vol. 30, no. 4, pp. 601–616, Jun. 2019, doi: 10.1177/0958305X18802766.

[39] A. Mehrpanahi, M. R. Aligoodarz, and M. Zandieh, “Comparative Energy and Exergy Analysis for the Utilization of Alternative Fuels in the Cement Kiln,” *Environ. Energy Econ. Res.*, vol. 4, no. 1, Feb. 2020, doi: 10.22097/eeer.2020.200433.1110.

[40] B. G. Emyat, “Energy Audit and Heat Recovery on the Rotary Kiln of the Cement Plant in Ethiopia: A case study,” *Int. J. Adv. Eng. Manag. Sci. (IJAEMS)*, vol. 5, no. 5, pp. 339–345, May. 2019, doi: 10.22161/ijaems.5.5.7.

[41] M. H. Nasution, I. R. Syahputra, and D. Rahman, “Energy and Exergy Analysis on the Rotary Kiln Unit of RKC-2 PT. Semen Gresik – Tuban Plant,” *Proc. Int. Semin. Chem. Eng. Soehadi Reksowardojo (STKSR)*, vol. 1143, no. 1, Apr. 2021, doi:10.1088/1757-899X/1143/1/012050.

[42] A. Atmaca and R. Yumrutaş, “Analysis of the parameters affecting energy consumption of a rotary kiln in cement industry,” *Appl. Therm. Eng.*, vol. 66, no. 1-2, pp. 435–444, May. 2014, doi: 10.1016/j.applthermaleng.2014.02.038.

[43] X. Ma, W. Shao, and Z. Cui, “Energy and thermodynamic analysis of a typical cement production system based on experimental and simulated investigations,” *Case Studies in Thermal Engineering*, vol. 38, Oct. 2022, Art. no. 102357, doi: 10.1016/j.csite.2022.102357.

[44] D. Song, L. Lin, and W. Bao, “Exergy conversion efficiency analysis of a cement production chain,” *Energy Procedia*, vol. 158, pp. 3814–3820, Feb. 2019, doi: 10.1016/j.egypro.2019.01.867.

[45] A. Atmaca and R. Yumrutaş, “Thermodynamic and exergoeconomic analysis of a cement plant: Part I – Methodology,” *Energy Conversion and Management*, vol. 79, pp. 790–798, Mar. 2014, doi: 10.1016/j.enconman.2013.11.053.

[46] T. J. B. Taweel, E. Sokolova, V. Sergeev, and D. B. Solovev, “Energy and Exergy Analysis of Clinker Cooler in the Cement Industry,” *IOP Conf. Series: Materials Science and Engineering*, vol. 463, Dec. 2018, Art. no. 032101, doi:10.1088/1757-899X/463/3/032101.

[47] H. G. Kandilci and H. Saraç, “Investigation of Energy Efficiency by Exergy Analysis in the Cement Sector,” M.S. thesis, Yıldız Technical University, Istanbul, Turkey, 2013.

[48] T. Engin and V. Arı, “Energy auditing and recovery for dry type cement rotary kiln systems – A case study,” *Energy Convers. Manag.*, vol. 46, no. 4, pp. 551–562, Mar. 2005, doi: 10.1016/j.enconman.2004.04.007.

[49] E. Mokrzycki and A. Uliasz-Bocheńczyk, “Alternative fuels for the cement industry,” *Appl. Energy*, vol. 74, no. 1-2, pp. 95–100, Jan. 2003, doi: 10.1016/S0306-2619(02)00135-6.

[50] V. Arı, “Energetic and exergetic assessments of a cement rotary kiln system,” *Sci. Res. Essays*, vol. 6, no. 6, pp. 1428–1438, Mar. 2011, doi: 10.5897/SRE11.030.

[51] Z. Utlu, Z. Söğüt, A. Hepbaşlı, and Z. Oktay, “Energy and exergy analyses of a raw mill in a cement production,” *Appl. Therm. Eng.*, vol. 26, no. 17-18, pp. 2479–2489, Dec. 2006, doi: 10.1016/j.applthermaleng.2005.11.016.

[52] Q. Yin, W.-J. Du, X.-L. Ji, and L. Cheng, “Optimization design and economic analyses of heat recovery exchangers on rotary kilns,” *Appl. Energy*, vol. 180, pp. 743–756, Oct. 2016, doi: 10.1016/j.apenergy.2016.07.042.

[53] B. G. Emyat, “Energy and Exergy Assessment and Heat Recovery on Rotary Kiln of Cement Plant for Cooling Effect Production by Using Vapor Absorption Refrigeration System,” *Iran. J. Energy Environ.*, vol. 11, no. 2, pp. 109–115, 2020, doi: 10.5829/ijee.2020.11.02.03.

[54] R. Nandhini, B. Sivaprakash, and N. Rajamohan, “Waste heat recovery at low temperature from heat pumps, power cycles and integrated systems – Review on system performance and environmental perspectives,” *Sustainable Energy Technologies and Assessments*, vol. 52, Aug. 2022, Art. no. 102214, doi: 10.1016/j.seta.2022.102214.

[55] E. Bani-Hani, M. El Haj Assad, M. Alzara, A. M. Yosri, Y. Aryanfar, H. G. Castellanos, S. Mohtaram, and A. Bouabidi, “Energy and exergy analyses of a regenerative Brayton cycle utilizing monochlorobiphenyl wastes as an alternative fuel,” *Energy*, vol. 278, Sep. 2023, Art. no. 127861, doi: 10.1016/j.energy.2023.127861.

[56] I.K. Kookos, Y. Pontikes, G. N. Angelopoulos, and G. Lyberatos, “Classical and alternative fuel mix optimization in cement production using mathematical programming,” *Fuel*, vol. 90, no. 3, pp. 1277–1284, Mar. 2011, doi: 10.1016/j.fuel.2010.12.016.