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RESEARCH ARTICLE

Detailed assessment of specific exergetic costing, energy consumption, and environmental impacts of a rotary kiln in cement industry

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Abstract

Türkiye is one of the biggest developing countries and the second biggest cement exporter in the world. In 2021, the country exported around $1billion of cement, which is responsible for over 8% of emissions globally. In order to fulfill the EU norms, energy, emissions, and cost reduction investments continue in the country. The aim of this paper is to perform a detailed exergoeconomic assessment of a rotary burner to increase the energy and exergy performance and decrease energy consumption, exergy costs and environmental impacts of a real scale cement factory in Türkiye. During the 2-year period, detailed data has been obtained from the factory by real time detection of clinker manufacturing process. By applying the specific exergy costing (SPECO) method, energy and exergy destructions, and exergetic cost distributions for the rotary burner are calculated in detail. The 1st and 2nd law efficiencies of the overall factory, specific energy (SEC) and exergy (SExC) consumption, and SPECO for clinker production are calculated to be 59.84%, 39.04%, 4786.75 MJ/ton, 5230.38 MJ/ton, and 10.11 $/MJ, respectively. The use of magnesia-spinel composite refractory bricks and the anzast layer formation decreased the SPECO by 2.71% corresponding to a saving of $2,280,000 preventing 13.74 $MtCO_2$ emissions yearly.

Keywords Cement industry · Energy efficiency improvement · Exergoeconomic analysis · Specific energy consumption · Environmental impacts · Emissions

Nomenclature

c	Cost per unit of exergy ($/GJ)
$\dot{C}$	Cost rate ($/h)
C_m	Payment in a year ($)
$\dot{D}$	Cost rate of exergy destruction
$\dot{E}$	Energy rate (kW)
$\dot{E}\alpha_k$	Fuel energy depletion ratio
$\dot{E}\beta_k$	Relative energy consumption ratio
$\dot{E}\chi_k$	Productivity lack ratio
$E\dot{I}P_k$	Energetic improvement potential
$\dot{E}x$	Exergy rate (kW)
$\dot{E}x_{dest}$	Rate of exergy destruction (kW)
$\dot{E}x_{heat}$	Rate of exergy transfer by heat (kW)
$\dot{E}x_{elect}$	Rate of exergy transfer by electricity (kW)
$\dot{E}x\alpha_k$	Fuel exergy depletion ratio
$\dot{E}x\beta_k$	Relative exergy consumption ratio
$\dot{E}x\chi_k$	Productivity lack ratio
$Ex\dot{I}P_k$	Exergetic improvement potential
f	Exergoeconomic factor
h	Enthalpy (kJ/kg)
i_{eff}	Effective rate of return (%)
$\dot{m}$	Mass flow rate (kg/s)
P_m	Present value of the payment ($)
$\dot{Q}$	Heat transfer rate (kW)
r	Relative cost difference
s	Entropy (kJ/kg K)
T	Temperature (K)
T_0	Ambient temperature (K)
w	Specific work (kJ/kg)
$\dot{W}$	Power (kW)
$y_{dest,}k$	Component exergy destruction over total exergy input
$y^*_{dest,k}$	Component exergy destruction over total exergy destruction
$\dot{Z}$	Cost rate associated with the sum of capital investment and O&M ($/h)

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$\dot{Z}^{CI}$ Cost rate associated with capital investment ($/h)
$\dot{Z}^{OM}$ Cost rate associated with O&M ($/h)

Abbreviations
CC Carrying charges
CRF Capital recovery factor
EXC Expenditure costs
MC Manufacturing costs
OMC Operating and maintenance costs
PEC Purchased equipment cost
SEC Specific energy consumption
SExC Specific exergy consumption
TCI Total capital investment

Subscripts
eff Effective
L Levelized
k Any component

Greek symbols
μ_I Energy efficiency
μ_{II} Exergy efficiency
ψ Specific flow exergy (kJ/kg)
τ Total annual operating times of units
σ Stefan-Boltzman constant as 5.67×10^{-8} W/m^2 K^4

Introduction

Cement industry is one of the main energy and cost intensive industrial sectors increasing the global emissions considerably. The sector is responsible for the 15% of the total global industrial energy consumption. Therefore, investigating energy intensive industries to transform them into sustainable sectors, which consume less energy and conserve the global resources, is a very important subject of current researches (Mahapatra et al. 2021; IEA 2021; Chen et al. 2010).

In 2020, global energy related CO_2 emissions are around 31.5 Gt, at the same year 4100 Mton cement is produced worldwide causing 2.5 GtCO_2 emissions which is responsible for 8% of global emissions (Cao et al. 2016).

Türkiye, which is one of the biggest developing countries with per capita ratio of 4.66 tCO_{2e} emissions, was included in Annex I and Annex II lists of the United Nations Framework Convention on Climate Change (UNFCCC) in 1992 due to her OECD membership.

The most important reasons for Türkiye's greenhouse gas emissions are originated from the combustion of coal in power stations and industrial sectors like cement industry. The country is the largest cement producer of Europe and the second biggest cement exporter in the world. In 2019, total export volume of Turkish cement increased by 68% to 23 million tons reaching a total value of $877 M (Ritchie and Roser 2020).

Because of the industrialization and growing populations, the global energy consumption trend has been increasing considerably causing severe environmental problems and climate change (Atmaca 2018b). Therefore, it is essential to perform energy, exergy, and exergoeconomic assessment of each energy intensive sectors to alleviate the unexpected results of energy consumption for a sustainable future (Çankaya and Pekey 2019).

The industry is one of the most polluting sector, consuming high amounts of fossil fuels to complete calcination of farine to produce clinker. A typical cement facility, which operates 24 h of a day (continuous process), consumes around 7–9 tons of lignite coal per h. Most of the studies in the literature calculated the SEC for cement production to be around 3.5–5 GJ/ton (Atmaca 2014).

There are several studies calculating the first law efficiency of different sections of a cement factory to minimize the inefficiencies and decrease the energy consumption rates (Tahsin and Vedat 2005; Kabir et al. 2010; Khurana et al. 2002; van Ruijven et al. 2016; Atmaca et al. 2012; Atmaca and Yumrutas 2015; Wang et al. 2021).

Worrell et al. (2000) have been offered use of roller mills, highly efficient separators, and suspension preheaters in rotary burners in dry cement manufacturing process to decrease the SEC for cement by up to 0.03–0.08 GJ/ton of cement.

Martin and McGarel (2001) proposed a methodology about the process control and management in raw mills and cement mills in cement industry to decrease the SEC for cement by 3–3.5 kWh/ton of cement.

A rotary burner with a daily production capacity of 600-ton clinker has been studied by Engin and Ari (2004). They found that about 40% of the energy is lost in grate clinker cooler system.

Simmons et al. (2005) offered the use of vertical roller mill for finish grinding to decrease the energy consumption by 16.9 kWh/ton of cement.

A raw mill has been investigated in detail by Atmaca and Kanoglu (2012) currently running in a factory located in Gaziantep. They calculated the SEC for farine and recommended to supply hot gas to the system from the pyroprocessing tower to increase the 1st law efficiency of the unit. The applications they offered reduced the raw mill energy consumption by 6.7% and saved 1.66 kWh/ton farine production.

Atmaca and Yumrutaş (2014a, b, c) have been calculated the first law efficiency of the same rotary burner in this study. They calculated the amount of the total energy lost in the system (12.5 MW) and the SEC for clinker production (3.73 MJ/kg). However, exergetic and exergoeconomic evaluations have not been performed in the study.

On the other hand, the number of studies evaluating the exergetic performance of a complete plant or a section of a facility is limited in number (Sogut et al. 2009).

Koroneos and Moussiopoulos (2005) assessed the exergetic performance of a cement plant in Greece. They revealed that around half of the total exergy loss is observed in the rotary kiln. They indicated that the greatest exergy loss (30%) have been observed in the preheating tower, grate clinker cooler and combustion of coal in the rotary burner.

Utlu et al. (2006) have been studied on a farine milling unit in cement industry. They evaluated the energetic and exergetic efficiencies to be 84.3% and 25.2%, respectively.

Seyyed and Saebi (2020) implemented a demand-side management (DSM) program that is applied by the Iranian energy ministry under the industrial operational reserve program (IORP) to reduce energy shortage during peak hours. They indicated that the program should be used for cement industry to increase the exergoeconomic efficiency of the plants.

Dirik et al. (2019) investigated the cement industry as being responsible for the largest part of the CO2 emissions from industrial activities. They analyzed environmental efficiency of the Turkish cement industry at firm level and attempt to reveal a comparison study under both output-oriented and non-oriented approaches with the aid of radial and non-radial Data Envelopment Analysis (DEA) models. They concluded that only 15.7% of all integrated cement factories are identified as being relatively efficient in all models.

Fierro et al. (2022) performed an exergo-economic comparison of waste heat recovery cycles for the cement industry. They studies 3 waste heat recovery technologies applicable in the cement industry. It is investigated that the Kalina cycles exhibit the lowest total exergy destroyed among all cycles.

Fierro et al. (2021) they have been performed a techno-economic assessment for a rotary kiln shell. The researchers have been proposed a waste heat recovery system and evaluated its feasibility considering electricity prices. They calculated a potential heat recovery of up to 4980 kW with an annulus absorber panel at the shell of the kiln.

However, there are very few publications and studies in literature evaluating the exergoeconomic performance of a cement factory (Anacleto et al 2021; Ghalandari et al. 2021).

A comprehensive exergoeconomic evaluation of a cement factory have been performed by Atmaca and Yumrutaş (2014a, b). The overall 1st and 2nd law efficiencies of the facility have been evaluated to be 59.37% and 38.99% respectively. SExC for clinker production is found to 133.72 USD/GJ.

Calculating the first law efficiency is not adequate to reach the best performance of a facility. Assessing the exergetic efficiency of a factory help the searchers understand and interpret the system from a different perspective. While the exergoeconomic evaluations supply valuable and detailed information about the consumption of financial resources in a facility.

There are some studies revealing and conducting the exergetic analysis performed all around the world.

Zhang and Jin (2022) have been gathered and analyzed 13,941 exergy-related publications during 1997–2020. Results show that three developing countries in Asia (China, Iran, and Türkiye) are the most productive countries, accounting for 45.87% of total studies.

In this research, an actual cement facility located in Türkiye has been investigated in detail. The methodology and formulations have been established for exergetic and exergoeconomic assessment of rotary burner currently running in the facility.

After calculating the 1st and 2nd law efficiencies of the unit, the SEC, SExC, and SPECO of farine, clinker and cement production are evaluated in detail. The required data have been collected during a 2-year investigation in the factory site.

Based on the literature research, this is the first paper presenting a comprehensive investigation to reveal the effects of the composition of refractory bricks and the anzast layer formation on the exergoeconomic performance of a kiln unit in cement industry.

Methodology

The exergoeconomic evaluation of a rotary burner in Gaziantep Cement plant in Türkiye has been investigated in detail to calculate the exergoeconomic performance of the unit.

The manufacturing capacity of the cement plant is around 1.4 million tons per year. The length and the diameter of the rotary burner is 59 m and 4.2 m respectively. The burner tube, which has around 67 ton of clinker production capacity, is inclined at an angle of 3.5° and rotates with 1.6 rpm. The factory uses a four cyclone pyro-processing tower to pre-calcinate the farine before entering the rotary burner (Atmaca 2018a).

The rotary burner is fired with pulverized coal increasing the inner temperature of the tube up to 1800 K to reach the sintering temperature of farine material. The grate clinker cooler gradually decreases the temperature of the hot clinker leaving the rotary burner using the ambient air. At the end of the process, cement mills are used to grind the clinker with additives (gypsum, pozzolans etc.) in required proportions to manufacture the desired type of cement. Figure 1 represents the flow chart of the plant.

During dry type cement manufacturing process, the water content of raw materials are kept as low as possible which makes the dry process more efficient than the wet process. The rotary kilns used in dry type cement manufacturing facilities have usually 5 zones (Fig. 2).

The coarse aggregate monolithic bricks are used for the chain zone which is at the front end of the burner. The longest zone is the preheating zone where the alkali resistant refractories (40 to

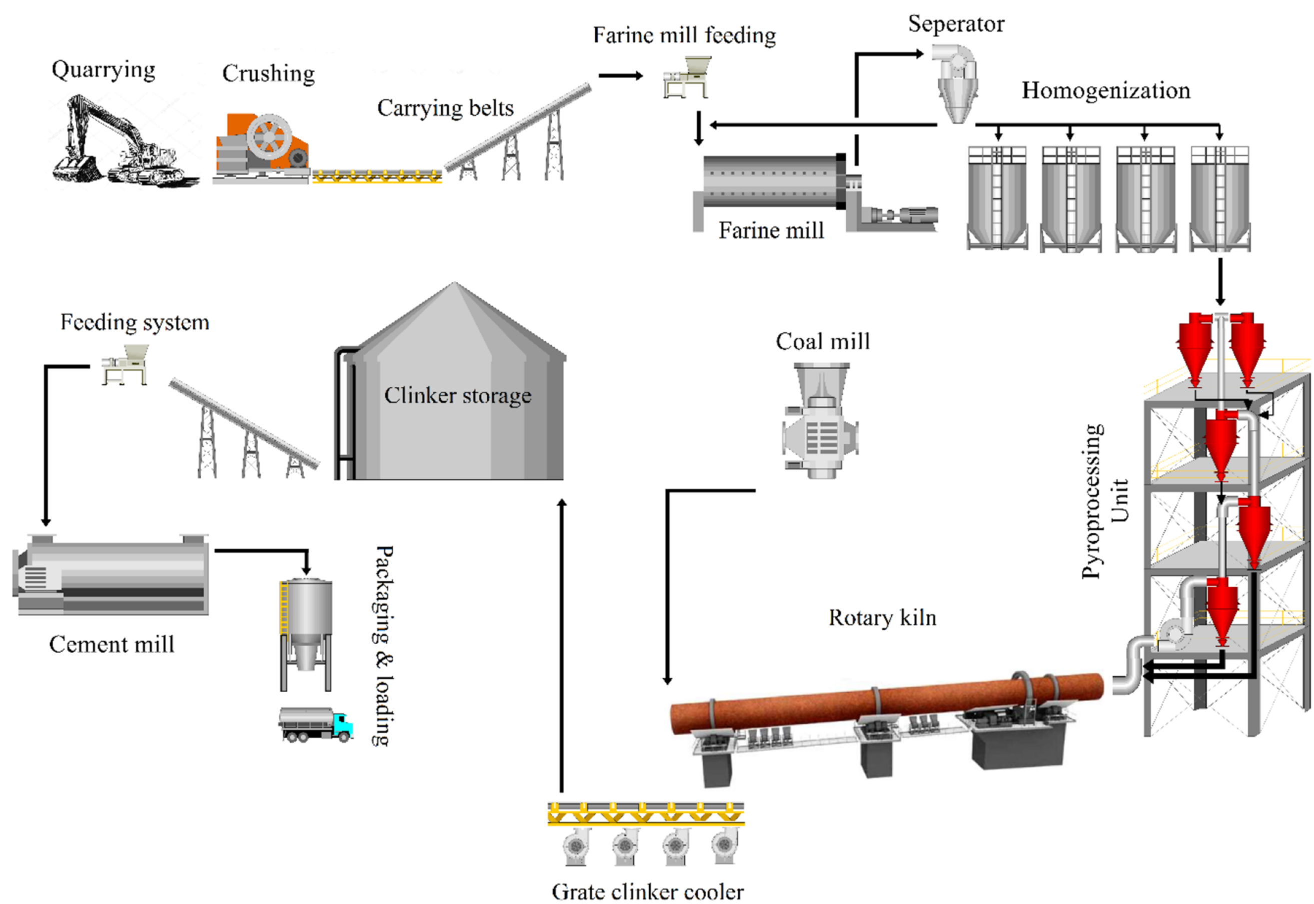


Fig. 1 Cement manufacturing process

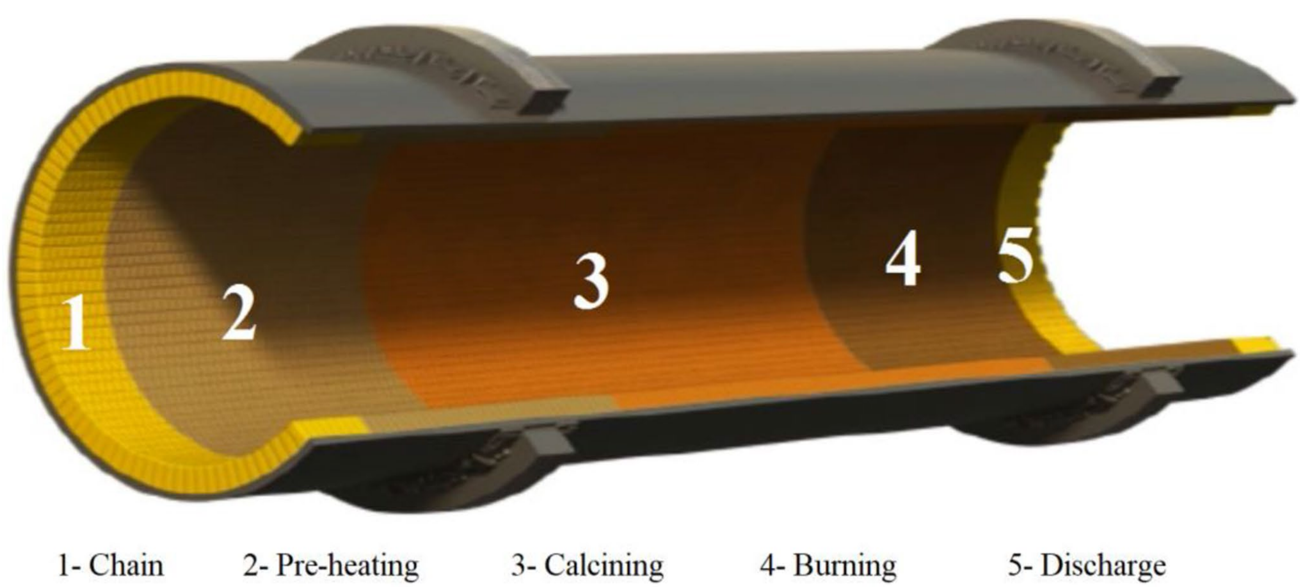


Fig. 2 The zones of the rotary burner

50% alumina bricks) are used. The temperatures in the calcining zone are higher than the other zones of the burner.

The refractories used in this zone must have the greatest thermal and physical properties. The inner temperature of the burner reaches up to 1400 °C in the burning zone where Magnesia-Alumina-Spinel bricks are used. There are three section in the burning zone, Upper Transition, Sintering and Lower Transition zones. Finally the discharge is the gate between the burner and the grate clinker cooler which is usually lined with alumina refractories (Atmaca and Yumrutaş 2014a, b, c).

The arrangement of bricks and the formation of anzast layer in the rotary burner are presented in Fig. 3. Figure 4 shows the details about the surface of the burner.

In order to analyze and optimize the rotary burner system and measure the SEC, SExC, and SPECO of the unit, massive data have been collected for 2 years by using online energy management system in the facility. During the thermodynamic evaluations, the following assumptions are made:

(1) the process within the rotary burner unit has a steady state, steady flow process,
(2) kinetic and potential energy chances are neglected,
(3) the hot gases within the system are assumed to be ideal,
(4) the surface temperatures of system components are assumed to be constant,
(5) ambient air conditions are supposed to be constant.
(6) complete combustion reaction is assumed in burner.
(7) the lower heating value (LHV) is used during the calculations.

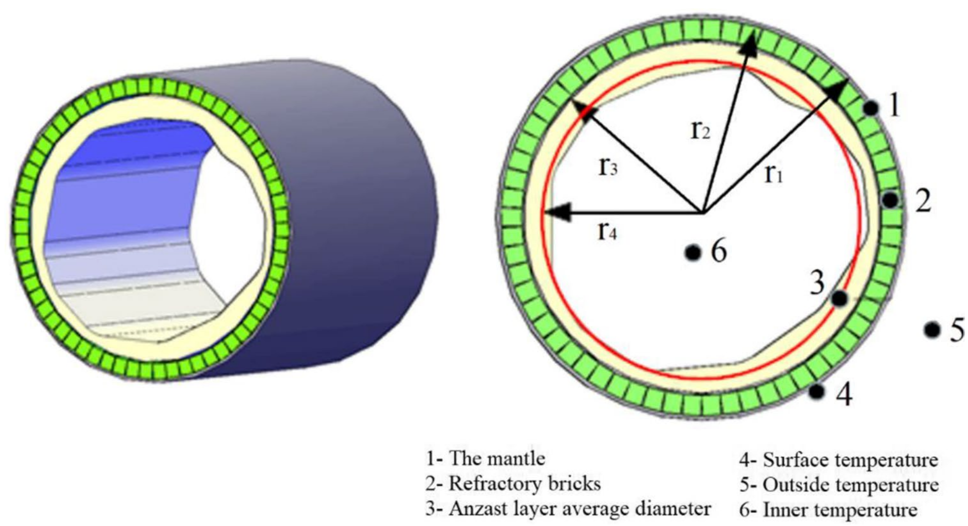


Fig. 3 The alignment of refractories and the formation of anzast layer

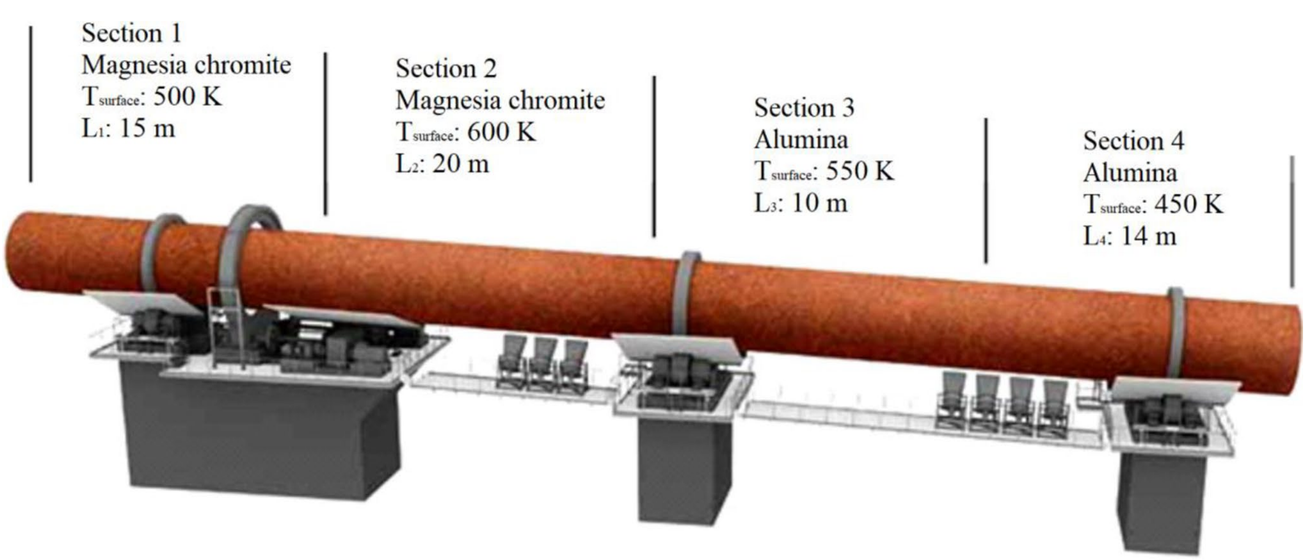


Fig. 4 The surface sections of the rotary burner

(8) mass flow rates of pre-calcined farine material and clinker, temperatures of each zone, surface of the mantle and materials are collected from online energy management system in the factory.
(9) the chemical and soil laboratory of the factory has been used during the calculation of the moisture rates and chemical compositions of the material streams,
(10) the electricity and fuel consumption values of the rotary kiln unit are read from the electricity panels and coal grinding and transport system which is precisely controlled by the online energy management system of the facility.

The rotary burner unit has the major share of energy consumption and therefore there are many opportunities in this unit to increase the efficiency and decrease the emissions and manufacturing costs of clinker and cement.

To calculate the performance of the rotary burner, detailed exergoeconomic and thermodynamic evaluations have been performed by taking detailed measurements and collecting significant data for a 2-year period in the factory site.

The methodology and detailed formulations about the SEC, SExC and SPECO calculations of the unit have been indicated in the following sections.

First law, second law analysis

The mass flow rates and thermodynamic properties of each material entering and leaving the system are determined. The 1st and 2nd law efficiencies of the system components, energy and exergy balances, and SEC and SExC values of each plant component are calculated by using the equations below.

The mass balance of the units are calculated by:

$$\sum \dot{m}_{\mathrm{in}} = \sum \dot{m}_{\mathrm{out}} \tag{1}$$

where $\dot{m}$ is the mass flow rate of the burner.

The energy balance of the burner is expressed as:

$$\sum \dot{E}_{\mathrm{in}} = \sum \dot{E}_{\mathrm{out}} \tag{2}$$

$$\dot{Q}_{\mathrm{net,in}} - \dot{W}_{\mathrm{net,out}} = \sum \dot{m}_{\mathrm{out}} h_{\mathrm{out}} - \sum \dot{m}_{\mathrm{in}} h_{\mathrm{in}} \tag{3}$$

The 1st law efficiency is calculated by:

$$\eta_I = \frac{\sum \dot{E}_{\mathrm{out}}}{\sum \dot{E}_{\mathrm{in}}} \tag{4}$$

The exergy balance of the system is:

$$\sum \dot{E}x_{\mathrm{in}} - \sum \dot{E}x_{\mathrm{out}} = \sum \dot{E}x_{\mathrm{dest}} \tag{5}$$

$$\sum \left(1 - \frac{T_0}{T_p}\right) \dot{Q}_p - \dot{W}_{\mathrm{net,out}} + \sum \dot{m}_{\mathrm{in}} \psi_{\mathrm{in}} - \sum \dot{m}_{\mathrm{out}} \psi_{\mathrm{out}} = \sum \dot{E}x_{\mathrm{dest}} \tag{6}$$

The subscript *dest* indicates destruction.

The 2nd law efficiency of the unit is defined by the following equation;

$$\eta_{II} = \frac{\sum \dot{E}x_{\mathrm{out}}}{\sum \dot{E}x_{\mathrm{in}}} \tag{7}$$

Internal energy change and enthalpy change of each substance are calculated by:

$$\Delta u = \int_1^2 c(T)dT = c_{\mathrm{avg}}\left(T_2 - T_1\right) \tag{8}$$

$$\Delta h = \Delta u + \upsilon \Delta P \tag{9}$$

the specific heat, specific volume, and pressure change is denoted by c_{avg},υ, and ΔP respectively.

The pressure change within the unit is negligible. Therefore, the enthalpy change is assumed equal to the change of internal energy of the system component.

The enthalpy of material streams within the system is calculated by:

$$\Delta h_{\mathrm{in}} = c_{\mathrm{avg}}\left(T_1 - T_0\right) \tag{10}$$

$$\Delta h_{\mathrm{out}} = c_{\mathrm{avg}}\left(T_2 - T_0\right) \tag{11}$$

where T_1 and T_2 are the input and output temperatures and c_{avg} is the average specific heat of the substances.

The entropy change for solids and liquids:

$$s_2 - s_1 = c_{avg} ln \frac{T_2}{T_0} \tag{12}$$

The entropy change for ideal gases:

$$\mathrm{s}_2 - \mathrm{s}_1 = \mathrm{c}_{\mathrm{p,avg}} ln \frac{\mathrm{T}_2}{\mathrm{T}_0} - \mathrm{R} ln \frac{\mathrm{P}_2}{\mathrm{P}_0} \tag{13}$$

where P is the pressure and c_p is the specific heat of the substance at constant pressure.

There is no pressure change within the system therefore, Δs values are calculated by:

$$\begin{aligned} \Delta s_{\mathrm{in}} &= c_{p,avg} ln \tfrac{T_1}{T_0} \\ \Delta s_{\mathrm{out}} &= c_{p,avg} ln \tfrac{T_2}{T_0} \end{aligned} \tag{14}$$

The exergy flows of each material in the rotary burner are calculated by:

$$\begin{aligned}\Delta\psi_{\text{in}} &= \Delta h_{\text{in}} - T_0\Delta s_{\text{in}} \\ \Delta\psi_{\text{out}} &= \Delta h_{\text{out}} - T_0\Delta s_{\text{out}}\end{aligned} \tag{15}$$

SEC and SExC analysis

The specific energy (SEC) and exergy (SExC) consumption for clinker production are calculated by the following equations,

The specific energy and exergy consumption for clinker production (SEC and SExC) is calculated by;

$$SEC_{clinker} = \frac{\dot{E}_t}{\dot{m}_c} \tag{16}$$

$$SExC_{clinker} = \frac{\dot{E}x_t}{\dot{m}_c} \tag{17}$$

where $\dot{E}x_t$ and $\dot{E}x_t$ are the total energy and exergy consumed during clinker production in the unit and $\dot{m}_c$ is the total clinker manufactured.

Energy balance and heat transfer calculations

The energy balance for the unit has been obtained by calculating the heat lost from the mantle of the rotary burner and the energy consumed during formation of clinker. The rotary burner unit is chosen as the control volume and it is investigated that the energy is transferred by mass (hot gas, farine, etc.), heat (waste heat, heat loss from the surface) and work (electrical work to drive the shaft of the rollers of the burner). It is observed that considerable amount of heat is lost from the exterior walls of the cyclones and the mantle of the burner.

There are three mechanism of heat transfer from the surface of the rotary burner, conduction, convection and radiation. In this study, in order to simplify the calculations, one dimensional heat transfer equations in cylindrical coordinates with constant conductivity values are used (Fig. 5).

The equations below are used to evaluate total heat transfer:

$$\dot{Q}_{\text{total}} = \frac{T_{\text{in}} - T_{\text{out}}}{R_{\text{total}}} \tag{18}$$

where R_{total} is the total thermal resistance of the unit and evaluated by:

$$R_{\text{total}} = R_{\text{conv,1}} + R_{\text{cond,1}} + R_{\text{cond,2}} + R_{\text{cond,3}} + \frac{R_{\text{conv,2}} \text{x} R_{rad}}{R_{\text{conv,2}} + R_{rad}} \tag{19}$$

The thermal resistances based on heat transfer mechanisms are calculated by:

$$R_{\text{conv,1}} = \frac{1}{2\pi r_4 L_1 h_1} \tag{20}$$

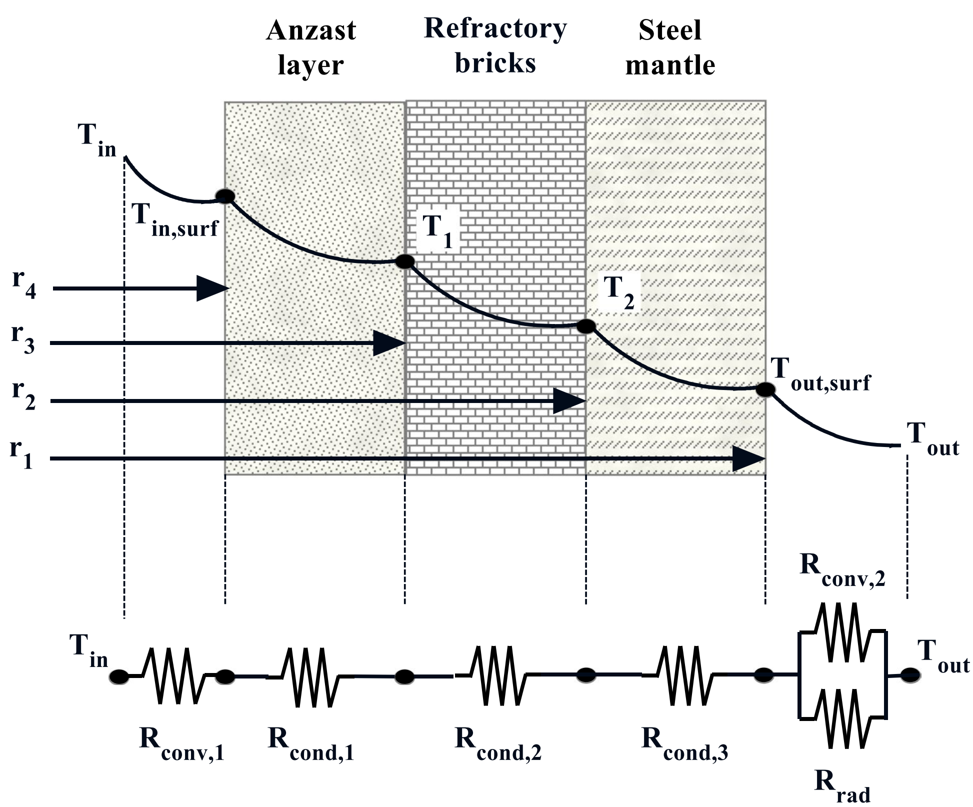


Fig. 5 The thermal resistance network for the burner

$$R_{\text{conv},2} = \frac{1}{2\pi r_1 L_1 h_2} \tag{21}$$

$$R_{\text{cond},1} = \frac{1}{2\pi L_1 k_1} ln \frac{r_3}{r_4} \tag{22}$$

$$R_{\text{cond},2} = \frac{1}{2\pi L_1 k_2} ln \frac{r_2}{r_3} \tag{23}$$

$$R_{\text{cond},3} = \frac{1}{2\pi L_1 k_3} ln \frac{r_1}{r_2} \tag{24}$$

$$R_{rad} = \frac{1}{2\pi r_1 L_1 h_{rad}} \tag{25}$$

where h, k, and h_{rad} are the convection coefficient, the thermal conductivity, and the radiation heat transfer coefficient respectively, h_{rad} is calculated from:

$$h_{rad} = \varepsilon\sigma\left(T^2_{\text{out,surf}} + T^2_{\text{out}}\right)\left(T_{\text{out,surf}} + T_{\text{out}}\right) \tag{26}$$

where ε and σ are the emissivity of the mantle and Stefan–Boltzman constant (5.67×10^{-8} W/m^2 K^4) respectively.

Beside the waste heat from the surface of the mantle, a rotary burner consumes high amounts of energy for the formation of clinker during the combustion process of pulverized coal. The chemical laboratory of the facility is used to see the chemical composition of the clinker manufactured (Table 1).

Al_2O_3, MgO, CaO, SiO_2, and Fe_2O_3 percentages in the cement produced have been measured to be 3, 1.76, 51.2, 26.5, and 4.5%, respectively. The equation of Strassen (1957) is used to calculate the formation energy of the clinker (FEc) in kcal/kg.

$$\begin{aligned}\text{FFc} =& 4.11\left[Al_2O_3\right] + 6.48[\text{MgO}] + 7.646[\text{CaO}] \\ &- 5.116\left[SiO_2\right] - 0.59\left[Fe_2O_3\right]\end{aligned} \tag{27}$$

Exergoeconomic calculations

In order to improve the energetic, exergetic, and cost performance of a system, exergoeconomic evaluations provide significant opportunities to the researches by combining exergy analysis with the economic rules.

The annual values of carrying charges, fuel costs, raw material costs, and operating and maintenance (O&M) costs are the necessary information used in the economic analysis of systems. The present value of components and materials change with time. Therefore, in this study the levelized annual value is used (Hermann 2006):

Table 1 The chemical composition of clinker

Name	Chemical structure	Chemical form	Percentage (%)
Calciumferrite	4CaO. Al_2O_3. Fe_2O_3	C_4AF	10.4
Di-calciumsilicate	2CaO.SiO_2	C_2S	13.2
Calciumaluminate	3CaO. Al_2O_3	C_3A	9.1
Tri-calciumsilicate	3CaO.SiO_2	C_3S	60.2
Potassiumoxide	K_2O	-	2.5
Sulfurtrioxide	SO_3	-	2.1
Magnesiumoxide	MgO	-	1.2
Sodiumoxide	Na_2O	-	1.3
Total	-	-	100

$$A = CRF \sum\nolimits_{m=1}^{n} P_m = \frac{i_{eff}\left(i_{eff}+1\right)^n}{\left(i_{eff}+1\right)^n - 1} \sum_{m=1}^{n} P_m \tag{28}$$

where CRF is the capital recovery factor and Pm is the present value of the payment ($).

$$P_m = C_m \frac{1}{\left(i_{eff}+1\right)^m} \tag{29}$$

where the rate of interest and payment period are denoted by i_{eff} and n, respectively.

During the exergoeconomic assessments of the system, the cost rate is evaluated by:

$$\dot{Z}_k = \left[\frac{CC_L + OMC_L}{\tau}\right] \frac{PEC_k}{\sum_k PEC_k} \tag{30}$$

where CC are the carrying charges, OMC operating and maintenance costs, PEC purchased equipment cost, and $\dot{Z}$ cost rate associated with the sum of capital investment and O&M ($/h).

Fuel levelized cost rate is calculated by:

$$\dot{C}_{EX} = \frac{EXC_L}{\tau} \tag{31}$$

where EXC_L is the levelized expenditure costs.

During the research, to compare the costs of each stream in the burner and understand the cost flow rates of each substance in the system, SPECO methodology is used (Xiang et al. 2004).

In this method, the exergy flows of each substance, fuels, and products of the burner are determined, and the cost equations are derived. Each exergy stream associated with a cost are expressed in the following equations:

$$\dot{C}_i = c_i \dot{E}x_i = c_i\left(\dot{m}_i \psi_i\right) \tag{32}$$

$$\dot{C}_e = c_e \dot{E}x_e = c_e(\dot{m}_e \psi_e) \quad (33)$$

$$\dot{C}_w = c_w \dot{E}x_w \quad (34)$$

$$\dot{C}_q = c_q \dot{E}x_q \quad (35)$$

The exergoeconomic balance equation for rotary burner system, consuming electrical energy and loosing heat energy from its surface is expressed as (Tsatsaronis and Pisa 1994):

$$\sum_i (c_i \dot{E}x_i) + c_w \dot{E}x_w + \dot{Z}_k = \sum_e (c_e \dot{E}x_e) + c_q \dot{E}x_q \quad (36)$$

In the SPECO methodology, to obtain auxiliary equalities, the fuels and products are defined by analyzing all exergy input and output from all the exergy flows, and the related costs are evaluated by applying basic principles. Exergetic cost balance is developed by equalizing the total costs of input and output streams of exergy.

Figure 6 presents an actual cement production facility. The mass, energy, exergy and cost balance are indicated in Table 2.

Exergoeconomic performance parameters

The performance parameters provide an opportunity for the researchers to compare, prioritize and improve the performance of the system components. The most common parameter is the exergoeconomic factor (f_k) which is used to identify the relationship between the cost of investment and the irreversibility within the system component.

The f_k value is calculated by the following equation (Xiang et al. 2004):

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k} \dot{E}x_{D,k}} \quad (37)$$

where $c_{f,k}$ is exergetic cost of fuel and $\dot{E}_{D,k}$ is the exergy destruction of the system.

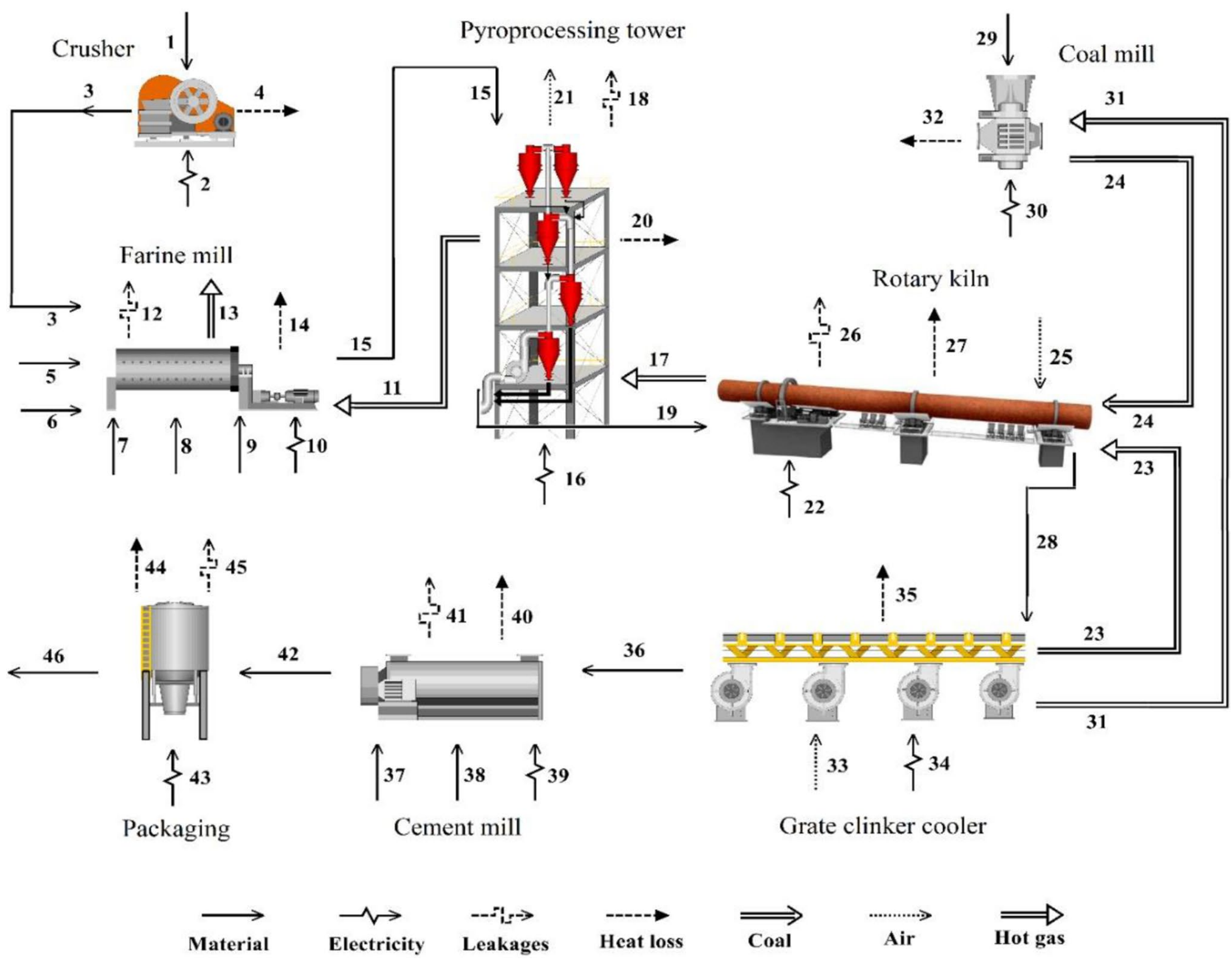


Fig. 6 Schematic of the actual plant

Table 2 Thermodynamic and SPECO equations for each unit of the facility

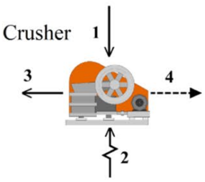
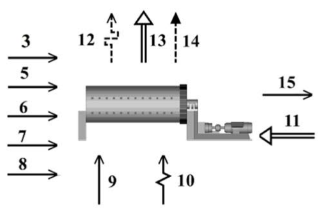
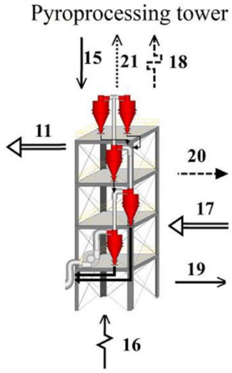
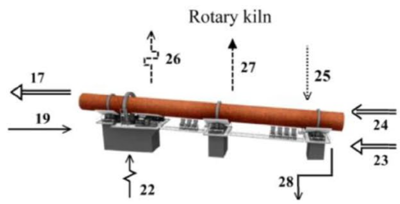
The units of the factory	The balance equations
Crusher 	$\dot{m}_1 = \dot{m}_3 = \dot{m}_{\lim estone}$ $\dot{E}_1 + \dot{E}_2 = \dot{E}_3 + \dot{E}_4$ $\dot{E}x_{dest} = (\dot{E}x_2 + \dot{E}x_1) - (\dot{E}x_3 + \dot{E}x_4)$ $\eta_I = \frac{\dot{E}_3}{\dot{E}_1 + \dot{E}_2}$ $\eta_{II} = \frac{\dot{E}x_3 + \dot{E}x_4}{\dot{E}x_1 + \dot{E}x_2}$ $\dot{C}_{W,Crusher} + \dot{Z}_{Crusher} + \dot{C}_1 = \dot{C}_3 + \dot{C}_{Q,4}$ $c_1 = c_3$
Farine mill 	$\dot{m}_3 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 + \dot{m}_{11} = \dot{m}_{12} + \dot{m}_{13} + \dot{m}_{15}$ $\dot{m}_{11} = \dot{m}_{13} = \dot{m}_{hotgas}$ $\dot{E}_3 + \dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_{10} + \dot{E}_{11} = \dot{E}_{12} + \dot{E}_{13} + \dot{E}_{14} + \dot{E}_{15}$ $\dot{E}x_{dest} = (\dot{E}x_3 + \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_9 + \dot{E}x_{10} + \dot{E}x_{11})$ $- (\dot{E}x_{12} + \dot{E}x_{13} + \dot{E}x_{14} + \dot{E}x_{15})$ $\eta_I = \frac{\dot{E}_{12} + \dot{E}_{13} + \dot{E}_{15}}{\dot{E}_3 + \dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_{10} + \dot{E}_{11}}$ $\eta_{II} = \frac{\dot{E}x_{12} + \dot{E}x_{13} + \dot{E}x_{14} + \dot{E}x_{15}}{\dot{E}x_3 + \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_9 + \dot{E}x_{10} + \dot{E}x_{11}}$ $\dot{C}_{W,Rawmill} + \dot{Z}_{Rawmill} + \dot{C}_3 + \dot{C}_5 + \dot{C}_6 + \dot{C}_7 + \dot{C}_8$ $+\dot{C}_9 + \dot{C}_{11} = \dot{C}_{12} + \dot{C}_{13} + \dot{C}_{Q,14} + \dot{C}_{15}$ $c_{11} = c_{13}$ $c_3 = c_5 = c_6 = c_7 = c_8 = c_9 = c_{12}$ $\frac{\dot{C}_{13}}{\dot{E}x_{13}} = \frac{\dot{C}_{11}}{\dot{E}x_{11}}$ (F)
Pyroprocessing tower 	$\dot{m}_{15} + \dot{m}_{17} = \dot{m}_{11} + \dot{m}_{18} + \dot{m}_{19} + \dot{m}_{21}$ $\dot{m}_{15} = \dot{m}_{18} + \dot{m}_{19} = \dot{m}_{farine}$ $\dot{m}_{17} = \dot{m}_{11} + \dot{m}_{21} = \dot{m}_{hotgas}$ $\dot{E}_{15} + \dot{E}_{16} + \dot{E}_{17} = \dot{E}_{11} + \dot{E}_{18} + \dot{E}_{19} + \dot{E}_{20} + \dot{E}_{21}$ $\dot{E}x_{dest} = (\dot{E}x_{15} + \dot{E}x_{16} + \dot{E}x_{17}) - (\dot{E}x_{11} + \dot{E}x_{18} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21})$ $\eta_I = \frac{\dot{E}_{11} + \dot{E}_{18} + \dot{E}_{19} + \dot{E}_{21}}{\dot{E}_{15} + \dot{E}_{16} + \dot{E}_{17}}$ $\eta_{II} = \frac{\dot{E}x_{11} + \dot{E}x_{18} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21}}{\dot{E}x_{15} + \dot{E}x_{16} + \dot{E}x_{17}}$ $\dot{C}_{W,Pyro} + \dot{Z}_{Pyro} + \dot{C}_{15} + \dot{C}_{17}$ $= \dot{C}_{11} + \dot{C}_{18} + \dot{C}_{19} + \dot{C}_{Q,20} + \dot{C}_{21}$ $c_{21} = 0$ $c_{17} = c_{11}$ $c_{15} = c_{18}$ $\frac{\dot{C}_{15}}{\dot{E}x_{15}} = \frac{\dot{C}_{19}}{\dot{E}x_{19}}$ (P) $\frac{\dot{C}_{17}}{\dot{E}x_{17}} = \frac{\dot{C}_{11}}{\dot{E}x_{11}}$ (F)

Table 2 (continued)



$$\dot{m}_{19} + \dot{m}_{23} + \dot{m}_{24} + \dot{m}_{25} = \dot{m}_{17} + \dot{m}_{26} + \dot{m}_{28}$$

$$\dot{m}_{19} = 0.58 \text{ x } \dot{m}_{28} = \dot{m}_{farine-clin\,\mathrm{ker}}$$

$$\dot{E}_{19} + \dot{E}_{22} + \dot{E}_{23} + \dot{E}_{24} + \dot{E}_{25} = \dot{E}_{17} + \dot{E}_{26} + \dot{E}_{27} + \dot{E}_{28}$$

$$\dot{E}x_{dest} = (\dot{E}x_{19} + \dot{E}x_{22} + \dot{E}x_{23} + \dot{E}x_{24} + \dot{E}x_{25}) - (\dot{E}x_{17} + \dot{E}x_{26} + \dot{E}x_{27} + \dot{E}x_{27})$$

$$\eta_I = \frac{\dot{E}_{17} + \dot{E}_{26} + \dot{E}_{28}}{\dot{E}_{19} + \dot{E}_{22} + \dot{E}_{23} + \dot{E}_{24} + \dot{E}_{25}}$$

$$\eta_{II} = \frac{\dot{E}x_{17} + \dot{E}x_{26} + \dot{E}x_{27} + \dot{E}x_{28}}{\dot{E}x_{19} + \dot{E}x_{22} + \dot{E}x_{23} + \dot{E}x_{24} + \dot{E}x_{25}}$$

$$\dot{C}_{W,Rotary} + \dot{Z}_{Rotary} + \dot{C}_{19} + \dot{C}_{23} + \dot{C}_{24} + \dot{C}_{25}$$

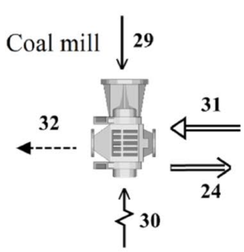
$$= \dot{C}_{17} + \dot{C}_{26} + \dot{C}_{Q,27} + \dot{C}_{28}$$

$$c_{25} = 0$$

$$c_{17} = c_{23}$$

$$\frac{\dot{C}_{19}}{\dot{E}x_{19}} = \frac{\dot{C}_{28}}{\dot{E}x_{28}} \text{ (P)}$$

$$\frac{\dot{C}_{24}}{\dot{E}x_{24}} = \frac{\dot{C}_{17}}{\dot{E}x_{17}} \text{ (F)}$$



$$\dot{m}_{29} = \dot{m}_{24} = \dot{m}_{coal}$$

$$\dot{E}_{29} + \dot{E}_{30} + \dot{E}_{31} = \dot{E}_{24} + \dot{E}_{32}$$

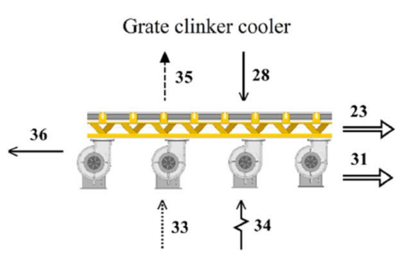
$$\dot{E}x_{dest} = (\dot{E}x_{29} + \dot{E}x_{30} + \dot{E}x_{31}) - (\dot{E}x_{24} + \dot{E}x_{32})$$

$$\eta_I = \frac{\dot{E}_{24}}{\dot{E}_{29} + \dot{E}_{30} + \dot{E}_{31}}$$

$$\eta_{II} = \frac{\dot{E}x_{24}}{\dot{E}x_{29} + \dot{E}x_{30} + \dot{E}_{31}}$$

$$\dot{C}_{W,Coalmill} + \dot{Z}_{Coalmill} + \dot{C}_{29} + \dot{C}_{31} = \dot{C}_{24} + \dot{C}_{Q,32}$$

$$\frac{\dot{C}_{29}}{\dot{E}x_{29}} = \frac{\dot{C}_{24}}{\dot{E}x_{24}} \text{ (P)}$$



$$\dot{m}_{28} + \dot{m}_{33} = \dot{m}_{23} + \dot{m}_{35} = \dot{m}_{hot-cold,clin\,\mathrm{ker}}$$

$$\dot{E}_{28} + \dot{E}_{33} + \dot{E}_{34} = \dot{E}_{23} + \dot{E}_{31} + \dot{E}_{35} + \dot{E}_{36}$$

$$\dot{E}x_{dest} = (\dot{E}x_{28} + \dot{E}x_{33} + \dot{E}x_{34}) - (\dot{E}x_{23} + \dot{E}x_{31} + \dot{E}x_{35} + \dot{E}x_{36})$$

$$\eta_I = \frac{\dot{E}_{23} + \dot{E}_{31} + \dot{E}_{36}}{\dot{E}_{28} + \dot{E}_{33} + \dot{E}_{34}}$$

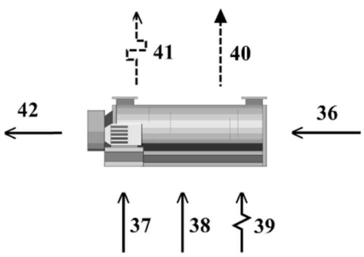
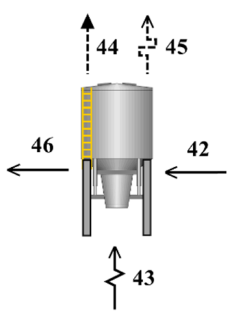
$$\eta_{II} = \frac{\dot{E}x_{23} + \dot{E}x_{31} + \dot{E}x_{36}}{\dot{E}x_{28} + \dot{E}x_{33} + \dot{E}x_{34}}$$

Another parameter is the relative cost difference (r_k) which is calculated to evaluate the relationship between the relative increase in cost for each exergy stream and the fuel cost. The parameter is calculated by:

$$r_k = \frac{c_{p,k} - c_{f,k}}{c_{f,k}} \tag{38}$$

The specific exergetic cost of the products and fuels are denoted by $c_{p,k}$ and $c_{f,k}$.

Table 2 (continued)

	$\dot{C}_{W,Cooler} + \dot{Z}_{Cooler} + \dot{C}_{28} + \dot{C}_{33}$ $= \dot{C}_{23} + \dot{C}_{31} + \dot{C}_{Q,35} + \dot{C}_{36}$ $c_{33} = 0$ $c_{36} = c_{28}$ $\frac{\dot{C}_{28}}{\dot{E}x_{28}} = \frac{\dot{C}_{36}}{\dot{E}x_{36}}$ (P)
Cement mill  	$\dot{m}_{35} + \dot{m}_{36} + \dot{m}_{37} = \dot{m}_{40} + \dot{m}_{41}$ $\dot{E}_{35} + \dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38} = \dot{E}_{39} + \dot{E}_{40} + \dot{E}_{41}$ $\dot{E}x_{dest} = (\dot{E}x_{35} + \dot{E}x_{36} + \dot{E}x_{37} + \dot{E}x_{38}) - (\dot{E}x_{39} + \dot{E}x_{40} + \dot{E}x_{41})$ $\eta_I = \frac{\dot{E}_{41} + \dot{E}_{42}}{\dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38} + \dot{E}_{39}}$ $\eta_{II} = \frac{\dot{E}x_{40} + \dot{E}x_{41} + \dot{E}x_{42}}{\dot{E}x_{36} + \dot{E}x_{37} + \dot{E}x_{38} + \dot{E}x_{39}}$ $\dot{C}_{W,Cementmill} + \dot{Z}_{Cementmill} + \dot{C}_{36} + \dot{C}_{37} + \dot{C}_{38}$ $= \dot{C}_{Q,40} + \dot{C}_{41} + \dot{C}_{42}$ $c_{37} = c_{38} = c_{41}$
Packaging  	$\dot{m}_{42} = \dot{m}_{46} = \dot{m}_{cement}$ $\dot{E}_{42} + \dot{E}_{43} = \dot{E}_{44} + \dot{E}_{45} + \dot{E}_{46}$ $\dot{E}x_{dest} = (\dot{E}x_{42} + \dot{E}x_{43}) - (\dot{E}x_{44} + \dot{E}x_{45} + \dot{E}x_{46})$ $\eta_I = \frac{\dot{E}_{45} + \dot{E}_{46}}{\dot{E}_{42} + \dot{E}_{43}}$ $\eta_{II} = \frac{\dot{E}x_{44} + \dot{E}x_{45} + \dot{E}x_{46}}{\dot{E}x_{42} + \dot{E}x_{43}}$ $\dot{C}_{W,Packaging} + \dot{Z}_{Packaging} + \dot{C}_{42} = \dot{C}_{Q,44} + \dot{C}_{45} + \dot{C}_{46}$ $\frac{\dot{C}_{42}}{\dot{E}x_{42}} = \frac{\dot{C}_{46}}{\dot{E}x_{46}}$ (P) $c_{42} = c_{45} = c_{46}$

The following equations express the cost rate of exergy destruction and ratio of exergy consumption of each component:

$$\dot{D}_{D,k} = c_{f,k}\dot{E}x_{D,k} \tag{39}$$

$$Ex\Lambda = \frac{\dot{E}x_{C,k}}{TCI_{\text{system}}} \tag{40}$$

where TCI is the total capital investment.

The relative irreversibility is:

$$Ex\beta_k = \frac{\dot{E}x_{C,k}}{\dot{E}x_{TC}} \tag{41}$$

The productivity lack ratio of each component of the facility is expressed as:

$$Ex\Gamma_k = \frac{\dot{E}x_{C,k}}{\dot{E}x_{UP}} \tag{42}$$

The exergetic improvement potential of each unit is calculated by:

$$Ex\dot{I}P_k = \left(1 - \mu_{II}\right)\dot{E}x_{C,k} \quad (43)$$

The exergy consumption rate of each component is expressed as:

$$Ex\Lambda = \frac{\dot{E}x_{C,k}}{TCI_{\text{system}}} \quad (44)$$

These parameters could be written with the energetic terms. The relative energy consumption ratio is:

$$E\beta_k = \frac{\dot{E}_{C,k}}{\dot{E}_{TC}} \quad (45)$$

The productivity lack ratio is:

$$E\Gamma_k = \frac{\dot{E}_{C,k}}{\dot{E}_{UP}} \quad (46)$$

The energetic improvement potential is:

$$E\dot{I}P_k = \left(1 - \mu_I\right)\dot{E}x_{C,k} \quad (47)$$

The ratio of energy losses of each component to total capital investment cost is:

$$E\Lambda = \frac{\dot{E}_{C,k}}{TCI_{\text{system}}} \quad (48)$$

Results and discussions

In this paper, the effects of the refractory bricks and formation of anzast layer on the performance of a cement facility is studied by calculating the SEC, SExC, MC and SPECO for clinker production.

The mass, energy, and exergy balances of each unit and the cost rates of each stream have been investigated by using a commercial software (MS Excel Professional Plus 2019) to investigate the overall factory. The results of this comprehensive investigation are discussed in this section.

Under standard conditions, the SEC and SExC values for the products of the factory have been calculated and discussed in the "First and second law analysis" section. The exergoeconomic evaluations of the factory have been assessed in the "SEC and SExC calculations" section. In the "The specific exergetic costing and plant performance calculations" and "The effects of the composition of refractory bricks and the formation of anzast layer" sections, the effects of anzast layer formation and the composition of refractory bricks on the on the energy, exergy and exergoeconomic performance of the plant have been evaluated and discussed in detail.

First and second law analysis

Pulverized lignite coal, which is burned in the rotary burners to complete the calcination process of farine, and electricity are the two major energy resources in a cement plant.

By using the equations presented in Table 2 and the real data obtained from the factory site, mass flow rates, temperatures, and energy and exergy rates of material flows have been evaluated and presented in Table 3. The data in presented in Table 3 have been used to calculate the 1st and 2nd law efficiencies of each component and presented in Table 4.

By the comprehensive investigations performed based on the real data and calculations, the overall 1st and 2nd law efficiencies of the facility are calculated to be 59.84% and 39.04% respectively. The same values for the burner are calculated to be 54.61% and 37.6%, respectively Table 5, 6 and 7.

SEC and SExC calculations

The rates of losses (energetic and exergetic) in the units of the factory are presented in Fig. 7. The SEC and SExC values for the products are calculated and presented in Table 8. The exergetic improvement potential and the ratio of energy losses to capital cost of the burner are calculated to be 34.56 MW and 348.4 kW/M$.

There are remarkable heat losses from the mantle of the rotary burner and the cyclones of the unit. It is realized that the energy (49.8 MW) and exergy loss (55.3 MW) in the rotary kiln are extremely high compared to the other units of the facility. This is because of the irreversible combustion process inside the rotary burner.

The rotary burner and the pyro-processing tower destructs around 62.03% and 22.9% of exergy input respectively. It is calculated that, the calcination of farine is responsible for the destruction of 84.9% of total exergy of the facility.

The specific exergetic costing and plant performance calculations

Detailed economic data of each component of the facility has been gathered to evaluate the exergoeconomic performance of the overall facility for 2 years. The SPECO of the units are evaluated by using Eqs. (28) to (36). The cost flow rates of each stream in the components of the facility are investigated.

Table 3 Mass flow rate, energy rates, temperature and exergy rates of each stream

State no	Fluid/power	ṁ (kg/s)	T (K)	Ė (kW)	Ėx (kW)
1	Coarse limestone	12.848	305	52.676	0.434
2	Crusher electrical power	–	–	250	250
3	Fine limestone	12.848	322	231.774	8.104
4	Crusher boundary heat loss	–	–	171.66	171.66
5	Marl	11.169	295	35.740	0.305
6	Clay	3.293	295	15.149	0.129
7	Iron ore	0.375	295	1.163	0.01
8	Bauxite	0.375	295	1.2	0.01
9	Moisture	4.174	295	87.246	0.744
10	Electricity	–	–	2000	2000
11	Hot gas	16.679	560	6530	1914.592
12	Air leakages	1.127	295	5.692	0.049
13	Hot gas exhaust	18.429	385	2538.656	342.716
14	Heat loss	–	–	2712.786	2712.786
15	Raw mix (farine)	33.148	385	3086.058	416.615
16	Electricity	–	–	5000	5000
17	Hot gas	18.541	1725	41,082.497	25,953.76
18	Air leakages	6.229	300	0	0
19	Hot farine	27.407	1011	19,681.321	9592.254
20	Heat loss	-	-	23,963.395	23,963.395
21	Exhaust	18.429	227	4191.961	1057.583
22	Electricity	-	-	4341.5	4341.5
23	Secondary air	24.698	1083.913	23,084.347	11,966.848
24	Coal	2	344	112.604	9.341
25	Primary air	2.768	290	88.368	4.278
26	Air leakages	3.135	710	1384.68	528.613
27	Heat loss	–	–	12,542.51	12,542.51
28	Hot clinker	16.667	1550	22,356.39	13,731.836
29	Coarse coal	2	310	22	0.359
30	Electricity	–	–	250	250
31	Hot gas	4.94	650	2143.743	723.011
32	Heat loss	–	–	275.153	275.153
33	Fresh air	47	313	607.035	12.784
34	Electricity	–	–	1873	1873
35	Heat loss	–	–	4510	4510
36	Cold clinker	17	390	1320.345	165.641
37	Gypsum	0.922	310	7.562	0.123
38	Limestone	0.986	310	7.297	0.119
39	Electricity	–	–	2202	2202
40	Heat loss	–	–	538.667	538.667
41	Air leakages	1.142	381	93.427	10.721
42	Cement	17.433	381	1440.314	165.279
43	Electricity	–	–	152	152
44	Heat loss	–	–	152.01	152.01
45	Air leakages	0.100	315	1.515	0.037
46	Finished cement	17.333	315	265.195	6.417

The exergoeconomic performance parameters (the relative energy loss, productivity lack ratio, energetic and exergetic improvement ratio, the ratio of energy loss to the total capital investment) have been calculated by using Eqs. (37) to (48).

Table 4 Energy and exergy losses, and 1st and 2nd law efficiencies of each unit of the facility

Units	$\dot{E}_L$ (kW)	$\dot{E}x_L$ (kW)	μ_I (%)	μ_{II} (%)
Crusher	123.58	245.54	59.17	1.95
Raw mill	2712.79	3118.41	70.65	22.04
Pyro-processing tower	23,963.40	20,445.09	49.91	34.25
Rotary kiln	49,847.18	55,395.25	54.61	37.60
Coal mill	275.15	333.68	88.61	65.72
Grate clinker cooler	2857.04	7635.10	90.01	59.98
Cement mill	799.78	2026.14	65.73	7.99
Packaging	123.58	245.54	59.17	1.95
Total	80,677.58	89,296.93	59.84*	39.04**

*1st law efficiency of entire factory

**2nd law efficiency of entire factory (the total fuel energy consumption including electricity and coal are calculated)

The electricity and coal (fuel) costs and capital costs including investment and O&M (operation and maintenance) expenditures are obtained from the management of the factory. During the SPECO calculations, the duration of production, interest rate, life span of the factory are assumed to be 8200 h, 7%, and 50 years, respectively.

Table 5 shows the purchased equipment costs (PEC), capital costs ($\dot{Z}_k^{CI}$) and O&M costs ($\dot{Z}_k^{OM}$) of each component of the facility.

By using the results in Table 3, the exergy transfer rates (material, power, heat transfer, leakages etc.) for each flow are evaluated and presented in Table 6.

Table 7 presents the results of the exergoeconomic calculations including exergoeconomic performance results of each unit under standard conditions. Figure 8 shows the total capital investment rate of each component of the cement facility.

The exergetic cost rate and the specific exergetic cost of the fuel input are evaluated be 1080 \$/h and 4.8 \$/GJ, respectively. The total investment rate of the factory is calculated to be 3587.08 \$/h. The exergoeconomic factor for crusher, coal mill and packing units are calculated to be 98.23, 97.59, and 98.77% respectively. It is determined that the PEC and O&M expenditures of these units must be decreased to increase the overall cost performance of the facility.

It has been observed that the exergoeconomic factor is quite low in the rotary burner (25.78%), pyro processing tower (34.31%) and grate clinker cooler (38.83%) units where the thermal losses and exergy destruction rates are significantly high compared to the other units of the facility. This is because of the fact that the exergetic destruction cost rate of these plant components are very high compared to their investment values.

Although the burner is the most expensive equipment of the factory (26\$M), the total investment rates of the cement mill and raw mill are too high to be neglected. This is due to the use of more advanced technology and the abundance of auxiliary equipment in milling systems in cement factories.

More importantly, milling systems are not working throughout the year. The annual operating hours of the grinding systems are less than that of the rotary kiln. The combustion systems are operated on a continuous process basis in order not to deteriorate the combustion regime, which decreases the quality of the clinker significantly.

The exergetic improvement potential of the burner is evaluated to be 34.5 MW, which is around 13.3 MW higher than the combined value of all other units. It is seen that there are significant opportunities for reducing costs and increasing overall system performance in the rotary burner. Total investment and destruction cost rates must be decreased in order to increase the exergoeconomic potential of the factory.

The SPECO, SEC, SExC, and MC of each product of farine, clinker and cement are calculated and presented in Table 8. It is calculated that the SExC during the production of farine is 2.11% higher than the SExC of cement

Table 5 The cost rates for each unit of the factory

Unit	PEC (\$)	$\dot{Z}_k^{CI}$(\$/h)	$\dot{Z}_k^{OM}$(\$/h)	$\dot{Z}_k^{T}$(\$/h)
Crusher	9,093,750	285.30	94.15	379.45
Raw mill	19,947,916	455.96	150.47	606.43
Pyroprocessing tower	22,864,583	446.14	147.23	593.36
Rotary kiln	26,156,250	510.37	168.42	678.79
Coal mill	10,593,750	282.50	93.23	375.73
Grate clinker cooler	5,187,500	101.22	33.40	134.62
Cement mill	19,781,250	452.15	149.21	601.36
Packaging	8,375,000	163.42	53.93	217.35
Installation, engineering, supervision, and other unexpected costs	37,000,000	-	-	-
TCI*	159,000,000	2,697.06	890.03	**3,587.08**

*Total capital investment

Table 6 The cost flow rates and the exergetic costs related to each exergetic flow

State	Unit	Material/energy/other	$\dot{C}$ (USD/h)	c (USD/MJ)
1	Crusher	Coarse limestone	2775.12	0.022
2		Electricity	25	0.028
3		Fine limestone	3162.71	2.469
4		Heat loss	17.17	0.028
5	Raw mill	Marl	2010.4	0.015
6		Clay	592.8	0.006
7		Iron ore	337.5	0.001
8		Bauxite	675	0.001
9		Moisture	222.75	0.037
10		Electricity	200	0.028
11		Hot gas	191.46	0.028
12		Air leakages	0	0
13		Hot gas exhaust	34.27	0.028
14		Heat loss	271.28	0.028
15		Raw mix (farine)	7087.13	4.725
16	P. Tower	Electricity	500	0.028
17		Hot gas	2595.38	0.028
18		Air leakages	0	0
19		Hot farine	7786.69	0.225
20		Heat loss	2396.34	0.028
21		Exhaust	0	0
22	R. Burner	Electricity	434.15	0.028
23		Secondary air	0	0
24		Coal	468.00	0.008
25		Primary air	0	0
26		Air leakages	0.00	0.000
27		Heat loss	1254.25	0.028
28		Hot clinker	8113.80	0.164
29	Coal mill	Coarse coal	23.04	0.002
30		Electricity	25.00	0.028
31		Hot gas	72.30	0.028
32		Heat loss	27.52	0.028
33	Cooler	Fresh air	0	0
34		Electricity	187.30	0.028
35		Heat loss	451.01	0.028
36		Cold clinker	7985.4	0.803
37	Cement mill	Gypsum	33.2	0.075
38		Limestone	35.5	0.083
39		Electricity	220.2	0.028
40		Heat loss	53.87	0.028
41		Air leakages	0	0
42	Packaging	Cement	8821.94	1.701
43		Electricity	15.2	0.028
44		Heat loss	15.2	0.028
45		Air leakages	0	0
46		Finished cement	9038.47	1.743

production. This is because of the difference in the mass flow rates of clinker and cement production.

The effects of the composition of refractory bricks and the formation of anzast layer

The most important unit of a cement facility is the rotary burner and the most important component of a rotary burner is the refractory materials used inside the burner. During the maintenance stop of the facility, it is investigated that magnesia chromite bricks are used inside the burner and these old refractory bricks are worn out and could not be used any more. The thickness and thermal properties of the old bricks have been decreased over the years.

In order to investigate the change of the performance of the factory, during the annual maintenance period of the facility, the old bricks are replaced with new refractory bricks, which have high Mg and Al content and resistance against high thermo-mechanical and thermochemical loads. Table 9 describes detailed information about the refractories.

The rotary kiln produces clinker on a continuous production basis. It is costly and undesirable to stop the production process. Therefore, the refractory bricks are replaced with new ones during the regular yearly maintenance of the factory. Meanwhile the formation of the anzast layer has been measured.

It is investigated that, the anzast layer behaves like a coating over the surface of the bricks protecting them against the effects of high temperature, supports the bricks, and reduces the energy loss from the burner surface and decreases fuel consumption. Silica has an abrasive effect on the bricks and prevents the formation of anzast layer.

Therefore, during farine production in the raw mill iron oxide minerals have been used instead of sand to reduce the amount of free silica. The materials containing higher silica were able to melt easily under lower temperature values. The qualified workers have a vital role to sustain the best conditions for clinker production.

Table 10 shows the change of SEC, SExC, MC, and SPECO for cement manufacturing after the replacement of new bricks, and obtaining a suitable anzast layer inside the rotary burner.

Figures 9 and 10 show the change of the amounts of clinker production and related coal consumption and the SEC, SExC, MC and SPECO for clinker production, respectively.

After the replacement of old bricks with new refractories and allowing the formation of anzast layer on the inner surface of the mantle of the kiln, the SEC (See Fig. 10) and coal consumption (See Fig. 9) have been decreased by 22% and 14.3% respectively.

Table 7 The results of exergoeconomic evaluations

Units	$\dot{Z}_{tot}$ (USD/h)	$\dot{D}_k$ (USD/h)	Exβ_k (%)	ExΓ_k (%)	ExIP$_k$ (kW)	ExΛ_k (kW/$M*)	*r* (%)	*f* (%)
Crusher	379.45	24.55	0.27	0.36	240.75	1.54	87.89	98.23
Raw mill	606.43	311.84	3.49	4.61	2,431.15	19.61	84.06	77.78
Pyroprocessing tower	593.36	2,044.51	22.90	30.23	13,442.76	128.59	3.06	34.31
Rotary burner	678.79	9,029.43	62.03	81.92	34,564.45	348.40	3.65	25.78
Coal mill	375.73	33.37	0.37	0.49	114.39	2.10	69.25	97.59
Grate clinker cooler	134.62	763.51	8.55	11.29	3,055.55	48.02	27.93	38.83
Cement mill	601.36	202.61	2.27	3.00	1,864.21	12.74	60.25	91.44
Packaging	217.35	9.77	0.11	0.14	91.65	0.61	61.75	98.77

*$M: 1 million USA dollars

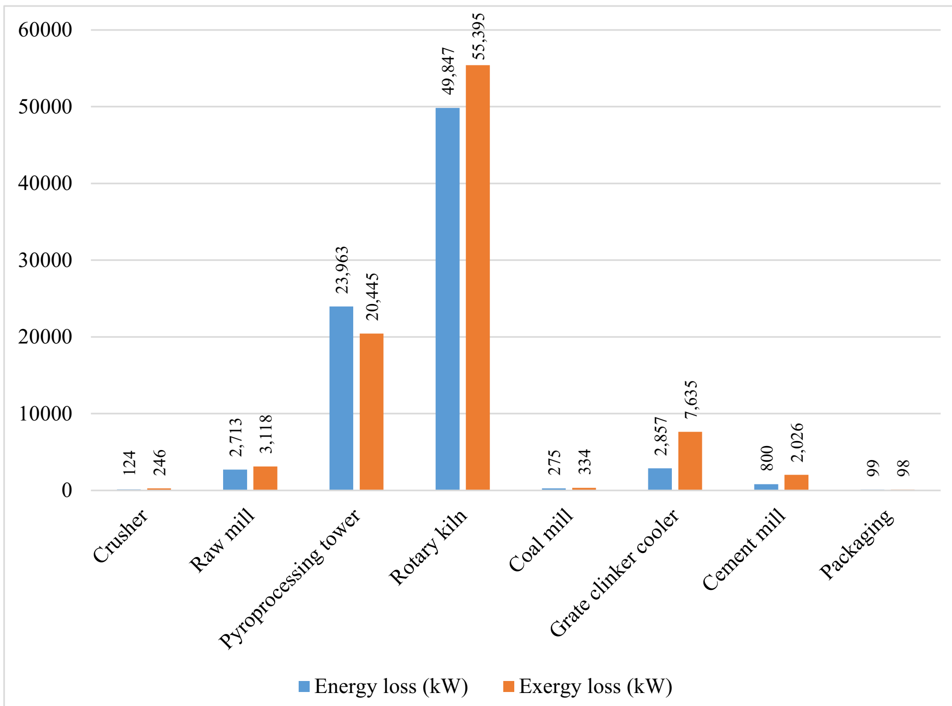


Fig. 7 The rates of energy and exergy losses in the units of the factory

Table 8 The SEC, SExC, MC and SPECO of farine, clinker, and cement under standard conditions

Material	Mass flow rate (kg/s)	Energy inlet (kW)	Exergy inlet (kW)	SEC (MJ/ton)	SExC (MJ/ton)	MCost ($/ton)	SPECO ($/MJ)
Farine	33.15	2,836.36	3,363.95	85.57	101.48	3.49	7.11
Clinker	16.66	73,466.18	80,868.76	4,410.32	4,854.71	23.38	10.11
Cement	17.42	74,365.33	82,992.69	4,267.96	4,763.09	33.08	13.50

Annual clinker production has been increased from 491,740 ton to 562,190 ton and coal consumption has decreased from 59,040 ton to 44,280 ton.

The SPECO of the facility has been decreased to 9.83 $/MJ corresponding to a saving of 0.28 $ per MJ of energy consumed by the system. The comparison of SEC for clinker production for selected countries are shown in Table 11

The effects of applications on the greenhouse gas emissions

Cement industry is the third largest industrial source of pollution emitting more than 500 Mtons/year of sulfur dioxide (SO_2), nitrogen oxide (NO_x), and carbon dioxide (CO_2). The

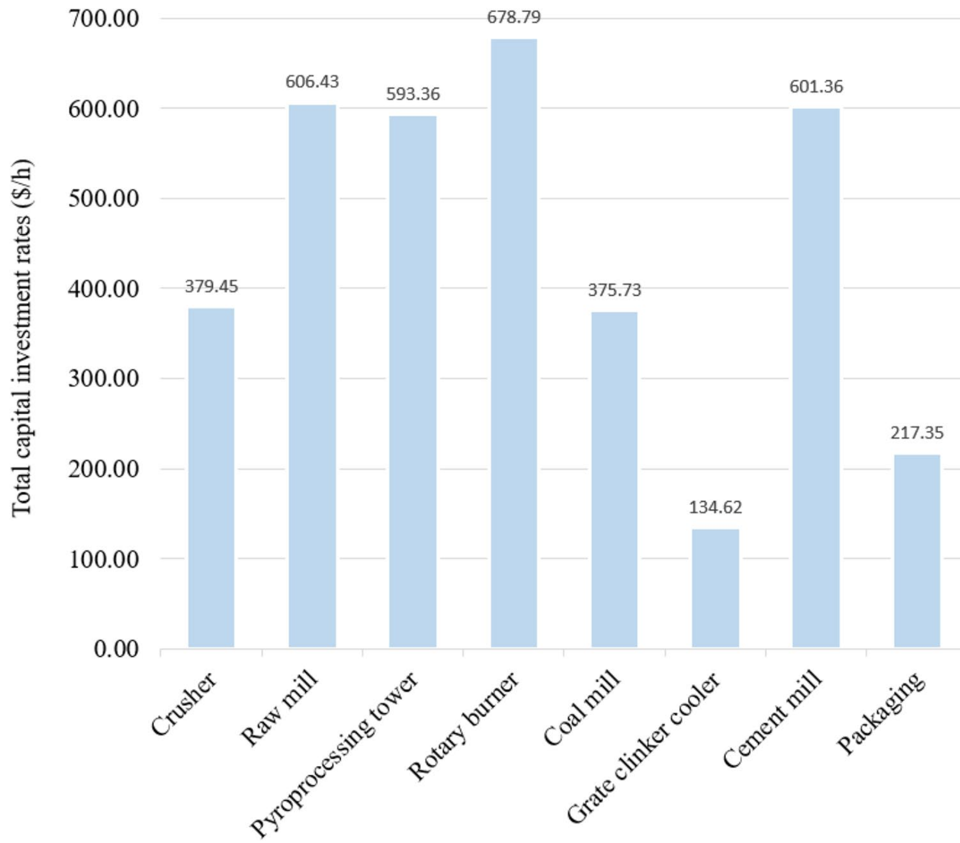


Fig. 8 The total capital investment rates of each component of the factory ($/h)

Table 9 Content of new refractory bricks

Content	Section 1 Magnesia Chromite	Section 2 Magnesia Spinel	Section 3 High alumina	Section 4 Alumina
Mg0 (%)	60–75	80–85	15–25	10–15
Al_2O_3 (%)	2–6	10–15	80–85	65–70
Cr_2O_3 (%)	2–6	–	–	–
CaO (%)	12–20	4–6	–	–
Fe_2O_3 (%)	–	–	5–10	3–10
SiO_2 (%)	4–6	2–5	3–9	5–15
Apparent porosity (%)	20	18	20	22
Bulk density (g/cm^3)	3.1–3.2	2.9–3.1	2.7–2.9	2.6–3.2
Thermal conductivity at 1000 °C (W/mK)	3.2	2.3	1.7	2.1
Cold crushing strength (MPa)	55	60	63	61
Thickness (mm)	250	300	350	250

Table 10 The SEC, SExC, MC, and SPECO of farine, clinker and cement after the replacement of new bricks, and obtaining a suitable anzast layer inside the rotary burner

Material	Mass flow rate (kg/s)	Energy inlet (kW)	Exergy inlet (kW)	SEC (MJ/ton)	SExC (MJ/ton)	MCost ($/ton)	SPECO ($/MJ)
Farine	33.15	2836.36	3363.95	85.57	101.48	3.49	7.11
Clinker	19.04	65,415.05	72,505.84	3434.86	3807.19	18.74	9.83
Cement	19.81	65,987.15	74,595.63	3330.87	3765.41	26.65	13.06

industry is one of the major sectors responsible for global warming.

CO_2 makes up the vast majority of greenhouse gas emissions from the sector, but smaller amounts of NOx and SO_2 are also emitted causing to significant health and environmental impacts for the last century.

NO_x emissions are one of the major sources of acid rain and global warming while deteriorating the quality of fresh water sources. SO_2 emissions affect the respiratory (asthmatics, bronchitis, emphysema) and cardiovascular systems of the creatures. CO_2 emissions have significant effects on the body's organs and tissues while increasing the ground-level ozone.

It is very urgent to calculate the environmental and health effects of the sector in detail, while providing methodologies and real life applications to decrease the overall impacts of the sector.

After the replacement of new bricks, and obtaining a suitable anzast layer inside the rotary burner, on-site measurements showed that the amount of clinker manufactured has been increased by 14.3%, from 491,740 to 562,190 ton. Meanwhile, the average coal consumption of the unit has

Fig. 9 The change of clinker production and related coal consumption

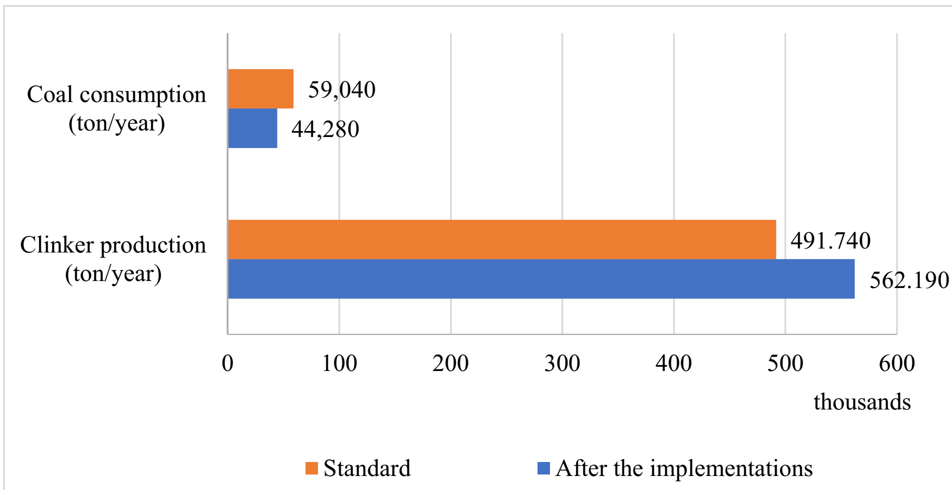


Fig. 10 The change of SEC, SExC, MC and SPECO for clinker production

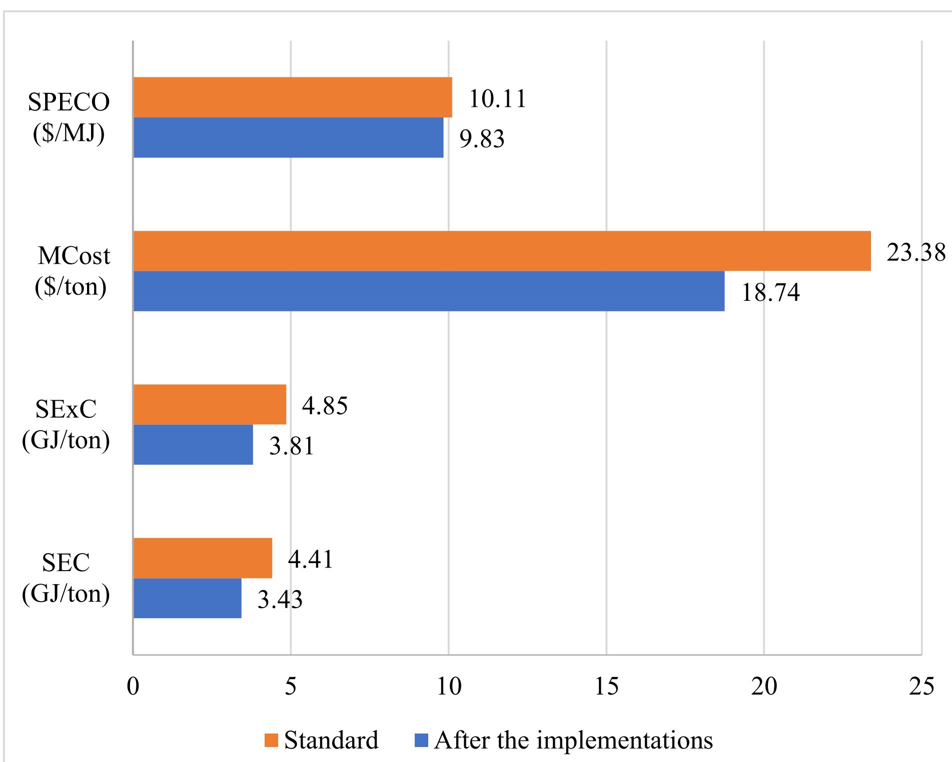


Table 11 Comparison of SEC for clinker production for selected countries around the world

Reference	Country	SEC (MJ/ton)
This study	Türkiye	3,430–4410
Alsalman et al. (2021)	USA	3300–3400
Kermeli et al. (2019)	Canada	3500–3800
Kusuma et al. (2022)	India	3200–4700
De Lena et al. (2022)	Spain	3500–4600
Brunke and Blesl (2014)	Germany	3300–3600
Madlool et al. (2013)	Japan	3400–3500
Ahmed et al. (2021)	Korea	3100–4600
Nidheesh and Kumar (2019)	Brazil	3000–4000
Sousa and Bogas (2021)	Italy	3600–3700
Ige et al. (2021)	China	3000–4000
Güereca et al. (2015)	Mexico	4190–4602
Vorayos et al. (2020)	Thailand	3498–3581
Average	World	**3386–4037**

decreased from 59,040 to 44,280 ton at the end of second year. The amount of coal saved per year is calculated to be 14,760 tons.

CO_2, NO_x, and SO_2 are the major greenhouse gases released during the combustion of coal in a rotary burner.

The specific CO_2 emission of coal is 0.93 ton CO_2/ton coal (Hrvoje et al. 2013). The type, N_2 content and combustion temperature of the fuel are some of the factors effecting the NOx emissions. The oxidation of nitrogen in the coal is responsible for the NO_x emissions. The emission factor for NO_x in clinker production is 1.4 kg/t coal.

The SO_2 emission factor of burner is 3.5S kg SO_2/ton of coal burned, where S is the sulfur content percentage in the coal. The SO_2 emissions per ton of coal burned in the facility is calculated to be sulfur content of the coal used in the factory is 0.0455 kg SO_2/ton coal. (Hrvoje et al. 2013).

The measurements showed that 13,727 tons of CO_2, 20.7 ton of NO_x, and about 0.7 ton of SO_2 emissions are prevented yearly which corresponds around 25% reduction in total emissions (Fig. 11).

Conclusions

Cement industry is one of the most energy and cost intensive sectors, which is responsible for around 15% of the global industrial energy consumption and 8% of total emissions (Zhang et al. 2021).

Coal consumption is one of the primary causes of emissions in Türkiye. The country is the largest cement producer of Europe and the second biggest cement exporter in the world.

Even though, the exergoeconomic analysis used on any plant to determine the avoidable exergy destruction and inversion cost rates in order to increase the rentability and sustainability of the factory, there are very few researches in literature evaluating the exergoeconomic performance of a rotary burner in a cement factory.

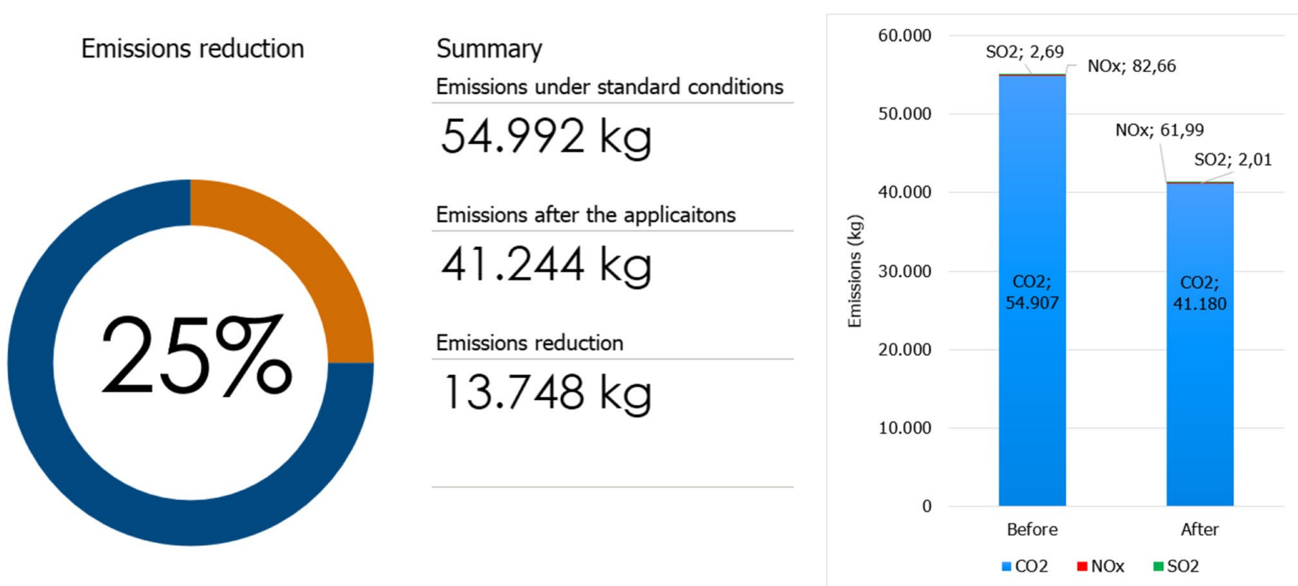


Fig. 11 Total emissions reduced after the implementations

In this research, the comprehensive thermodynamic and exergoeconomic analysis of the rotary burner unit in a cement facility showed that the overall performance of a cement factory significantly depends on the rotary burner unit, which is responsible for the major portion of the energy and exergy losses because of the clinker formation during coal burning.

The following conclusions have been drawn from the detailed assessment of the overall cement facility.

- The overall first law efficiency of the cement facility and the rotary kiln is determined to be 61.78% and 57.93% while the second law efficiencies are 40.79% and 40.47% respectively.
- 43.5 MW of energy (58.5% of overall energy lost) and 49.1 MW (59.1% of overall exergy lost) of exergy is lost during clinker formation in the rotary burner.
- For clinker production, the SEC, SExC, MC, and SPECO are evaluated to be 4,410.32 MJ/ton, 4,854.71 MJ/ton, 23.38 $/ton, and 10.11 $/MJ, respectively.
- It is investigated that the thickness and thermal properties of the refractory bricks are essential parameters effecting the coal consumption and related emissions. The refractories with high Mg and Al content and resistance against high thermo-mechanical and thermochemical loads have notably potential on the energy consumption of the overall system. The replacement of old refractory lining with magnesia spinel refractory bricks having better thermal and physical properties and the formation of anzast layer have increased the overall efficiencies of the factory (64.02% and 41.87%) and rotary kiln (61.02% and 42.4%).
- It is calculated that the total energy and exergy destruction of the factory are decreased by 11.26% (65.98 GW) and 10.12% (74.59 GW) respectively.
- The SEC, SExC, MC, and the SPECO of the rotary burner have been decreased by 22.11%, 21.57%, 19.83%, and 2.71% respectively.
- The clinker production of the unit has been increased by 14.32% and the fuel consumption of the burner has been decreased by 25.01% at the end of the year.
- After the implementations, annual coal consumption has been reduced by 14,760 tons, which reduces the annual CO_2, NO_x, and SO_2 emissions rates by 13,727 tons, 20.66 tons, and 672 kg, respectively. The implementations resulted in around 25% reduction in total yearly emissions of the rotary kiln.
- The applications reduced the specific cost of cement production by 4.64 $/ton corresponding to a saving of $2.28 M/year.
- The performance of the overall factory should be increased by increasing the combustion efficiency. The insulation of cyclones and the mantle of the burner, minimizing the leakages of hot gases circulating within the system, and performing periodical maintenance for all the units of the facility can help decrease energy consumption and manufacturing costs.
- Further investigations may focus on the operational parameters of grate clinker cooler systems affecting the overall exergoeconomic performance of a cement factory.

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Author contribution Dr. Atmaca contributes as the only writer and reviewer of the research. He contributes in writing up all technical sections of the manuscript.

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Declarations

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Consent to participate Not applicable.

Consent to publish Not applicable.

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