Energy Efficiency (2023) 16:36
https://doi.org/10.1007/s12053-023-10112-w

ORIGINAL ARTICLE

A comprehensive investigation of a grinding unit to reduce energy consumption, environmental effects and costs of a cement factory, a case study in Türkiye

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Received: 11 January 2022 / Accepted: 7 April 2023 / Published online: 3 May 2023

Abstract Türkiye is the largest cement producer of Europe and the second biggest cement exporter in the world. The industry is responsible for more than 8% of global carbon dioxide (CO_2) emissions and around 15% of the primary energy consumed worldwide. In this paper, the specific energy consumption (SEC) and related emissions of a real scale cement factory currently running in Türkiye have been decreased by investigating the effects of moisture rate of the raw materials and the hot gas transfer to the grinding unit. The data has been collected in the factory site by using the monitoring equipment and real time detection over a 24-month period. Energy and exergy destructions and exergetic cost distributions are determined by using specific exergy costing method (SPECO) for all units of the factory. The specific exergetic consumption (SExC) and production (MC) costs of raw meal are calculated to be 5.05 $/GJ and 4.13 $/ton, respectively. It is investigated that the hot gas supply to the grinding unit and decreasing the moisture rate of feeding materials decreased the SPECO of raw meal, clinker and cement by 8.25%, 5.49% and 4.89% respectively. The applications provide 184.69 MJ reduction in specific energy consumption (SEC) per ton of cement produced and blocked 75,343.37 tons of CO_2 emissions per year and reduced the cement production cost to 40.47 $/ton corresponding to a saving of $2.06 M per year. It has been demonstrated that it is very important to keep the moisture content of raw materials used in the cement industry as low as possible in terms of reducing energy consumption and manufacturing costs for sustainable production.

Keywords Cement industry · Energy efficiency · Exergy efficiency · Grinding · Advanced exergy analysis · Thermoeconomic analysis

Introduction

Growing population, industrialization and consumption trends around the world have been increasing the global energy consumption, which has direct and indirect effects on human health and ecology.

Cement industry is one of the main sectors effecting the global energy consumption and related emissions considerably. The grinding systems, which have been used in raw meal and cement production since 18th century, are also the major auxiliary equipment and electrical energy consumers in cement plants. Around 2% of the electrical energy produced globally is consumed during the grinding process in cement

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Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s12053-023-10112-w.

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industry (IEA, 2019). For 1 ton of cement around 360 MJ of electricity is used and 250 MJ of this energy is used during grinding process (Dirik et al., 2018). The industry is one of the worst pollutant sectors in the world (Yue et al., 2021). The specific carbon dioxide (CO_2) emissions intensity for cement is around 0.59 $kgCO_2$ per kg of cement (Atmaca & Yumrutaş, 2015).

For the last 50 years specific energy consumption during cement production has been decreased by 30% (7.8 GJ/ton to 5.5 GJ/ton) while the cement production increased from 0.5 to 4.2 Gt/year in 2019 (Kenneth, 2020). Consequently, around 8% of global CO_2 emissions originate from the cement industry. Therefore, it is important to optimize all the main energy-consuming components in cement production process (Hasanbeigi et al., 2010; Touil et al., 2006).

Many researchers have been used the 1st law of thermodynamics to investigate the energetic performance of a system, however this approach is incapable of assessing the energetic quality (exergy). Exergy is related with the 2nd law of thermodynamics (Kwon et al., 2001; Silveira & Tuna, 2003). The property is referenced to define the availability of a certain amount of energy at a certain state. Exergy describes the thermodynamic value of a given quantity of energy and becomes a powerful tool when it is studied with exergoeconomic assessment, which supplies valuable data to create cost effective systems (Erbay & Koca, 2012; Rosen et al., 2005). In this paper, SPECO method is used for the exergetic assessment of the raw mill.

In this method, fuels and products are classified by categorizing input and output exergy streams of each material (Lazzaretto & Tsatsaronis, 2006). Each exergy unit of all the streams entering and leaving the system borders have been allocated with a cost value.

There are different exergoeconomic approaches applied to various systems in the literature (Hua et al., 1997; Ozgener, 2007; Rosen & Dinçer, 2003; Zhang et al., 2000). However, none of them focused on raw mills evaluating its overall exergetic and exergoeconomic effects in cement factories.

Hossain et al. (2020) investigated the energy management practices in the cement industries of Bangladesh. They concluded that the energy management practices could increase the energy efficiency by 5%.

Tesema and Worrell (2015) calculated the energy intensity of cement factories in Ethiopia by identifying 26 energy efficiency measures. They calculated the cost-effective energy saving potential to be 159 GWh for electricity and 7.2 PJ for coal.

Atmaca and Kanoglu (2012) has been investigated a raw mill in Gaziantep, Türkiye. They calculated the 1st and 2nd law efficiencies of the system to be 61.5 and 16.4%, respectively. The SEC for raw meal is calculated to be 89.1 kJ/kg.

Utlu et al. (2006) focused on a raw mill to increase the 1st and 2nd law efficiencies of a raw meal system of a factory in Türkiye. Utlu & Hepbasli (2007) has been evaluated the efficiency of a trass mill used in the same factory.

Engin and Ari (2004) investigated a rotary burner producing around 600,000 kg clinker/day. The researchers calculated that the hot flue gas and cooler stack are responsible for around 40% of the energy lost.

Koroneos and Moussiopoulos (2005) focused on a plant in Greece. During exergetic assessment of the system, the energy and exergy input rates have been investigated for each state. They found that, the calcination process is responsible for 50% of the exergy lost in the system.

Atmaca and Yumrutaş (2014) have been performed a detailed thermodynamic and exergoeconomic analysis on a factory. They calculated the overall efficiencies, the exergy destructions and exergetic cost allocations of the factory by using SPECO methodology. They found the SExC and MC for raw meal, clinker and cement produced. However, they were not mentioned about the effects of different operational parameters on the SEC, SExC, MC and SPECO results of the entire plant.

Fierro et al. (2022) compared waste heat recovery cycles in the cement industry by applying exergo-economic methodologies. However, they did not focus on the raw meal system in the facility. The results of the study showed that lowest exergy is destructed by using Kalina cycle during the process.

There are very few publications and studies in literature evaluating the exergoeconomic performance of a cement facility.

Anacleto et al. (2021) evaluated the chemical exergy and Pre-calcination effect on a rotary kiln in Brazil. They calculated the exergetic efficiency considering all the chemical exergy contributions to be 55.5%, while considering just the fuel chemical exergy the exergetic efficiency of the classical burner is calculate dot be 22.6%.

Ghalandari et al. (2021) calculated the energy and exergy efficiency of an industrial-scale vertical roller mill (VRM) of Kerman Momtazan Cement Company in Iran. The energetic and exergetic efficiency values of the VRM is calculated to be 62.1% and 34.6% respectively.

Apart from the previous studies, in this study, a horizontal raw meal mill currently running in an actual cement plant is considered and comprehensive formulations for exergoeconomic assessment for the system are established. The energetic and exergetic efficiencies, the SEC, SExC, MC and SPECO of products and plant components have been investigated in detail. The effects of hot gas supply and the moisture rate of feeding materials on the exergetic and exergoeconomic performance of the factory have been studied in detail.

The literature review shows that, this study is the first comprehensive exergoeconomic investigation revealing the effects of raw mill operational parameters in cement industry and can contribute to a better understanding of raw meal manufacturing parameters affecting the overall exergetic and cost performance of a cement factory.

System description and methodology

Cement manufacturing process

Cement production includes four main stages:

- mining and grinding raw materials to produce raw meal and blending it in homogenization silos before preheating process in pyroprocessing tower,
- pre-calcination of raw meal with hot gases sucked from the rotary kiln,
- rotary kiln process to calcinate the raw meal and form clinker,
- grate clinker cooler system to cool and send the clinker for final grinding process in a cement mill.

Around 90% of the thermal energy is consumed in the rotary kiln and 90% electrical energy is consumed in milling processes.

In this research, a cement manufacturing factory located in Gaziantep city is chosen as a case study for the evaluation of exergoeconomic performance of the overall plant.

Every year, the plant produces about 1,400,000 ton cement. The factory has been using dry process during manufacturing of Portland cement. The factory uses a refractory lined tube type rotary kiln which has a diameter of 4.2 m and 59 m length and rotates with 1.6 rpm. The rotary burner has a clinker production capacity of 65–70 ton/h. In order to pre-calcinate raw meal, a cyclone type pre-heater consisting of 4 stages is used. Raw meal is heated to a sintering temperature as high as 1750 K in the kiln. Clinker is produced after the complete calcination of raw meal inside the kiln. The temperature of the clinker is decreased gradually in a grate cooler system. Finally, based on the type of the cement produced, pozzolans, gypsum and some additives are ground with clinker. Figure 1 shows the flow diagram of a plant.

Raw meal production process

Raw meal grinding systems are used to pulverize the input materials to produce raw meal. Raw meal is burned in the kiln where the calcination process is completed and clinker is produced. The raw mill investigated in this study is a horizontal mill with one chamber. The circulation of raw meal and return materials is achieved by using a mechanical circulation system to grind 140–170 ton of feeding materials per hour. The detailed specifications of the mill is indicated in Table 1.

Figure 2 presents the schematic of the grinding system including a steel elevator with buckets. The raw materials (limestone, clay, marl and iron ore) are transported to the bunkers and weighed before entering the grinding system. The separator is used to convey the oversized material back to the grinding system. The feed rate of raw meal mill is proportionally effected by the amount of recirculating material. Up to 50% of moisture rate of the feeding materials can be decreased by using an external hot gas supply system.

System analysis

Data collection and assumptions

The required data collected from the factory site by the operators for process control and optimization using online data collecting computers in 2019 and

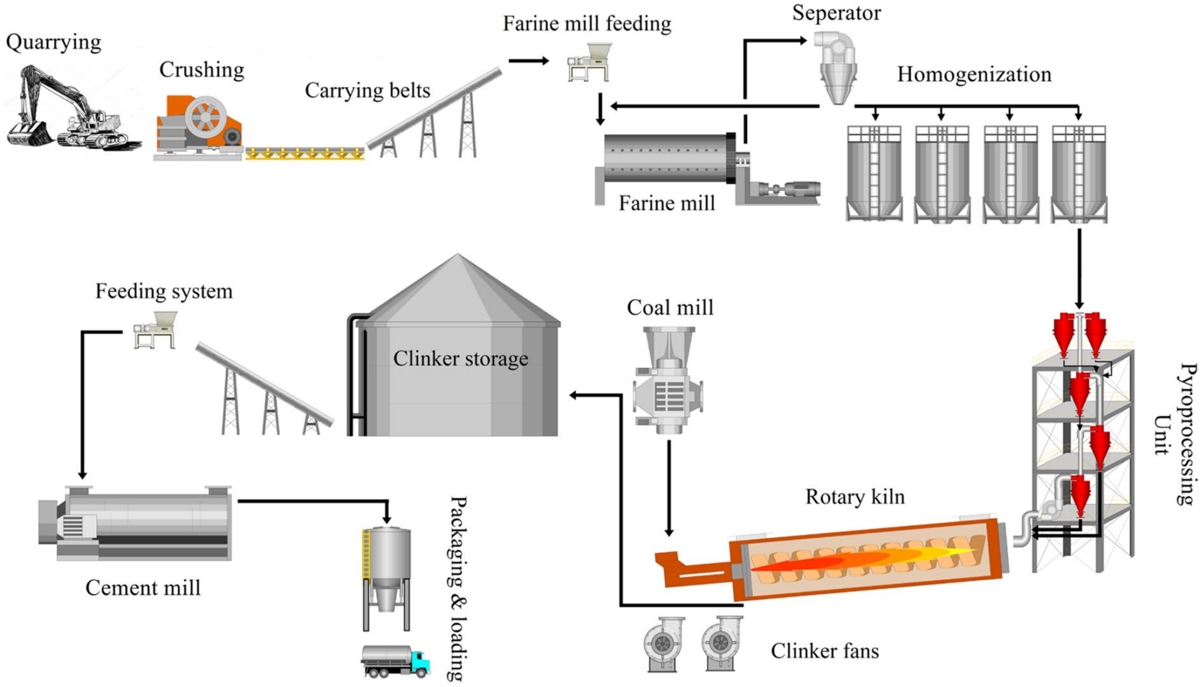


Fig. 1 Cement manufacturing process

2020. All the mechanical and operational parameters are controlled and observed by online system in the facility.

Massive data have been collected for 24 months to examine the entire factory.

The following assumptions are made during the calculations:

- All the units of the cement facility have steady state, steady flow processes.
- Ambient air conditions are supposed to be constant.
- The gases in any unit are accepted to be ideal gases.
- A complete combustion reaction is assumed in burner.
- During calculations for each unit lower heating value (LHV) is used.
- The mass flow rates of limestone, iron ore bauxite, clay, the hot gas supply and raw meal produced are gathered from online recorder in the grinding facility.
- The environmental and the feeding materials' temperatures, hot gas and the surface temperatures of the mantle of the system are measured by the process control programs and recorded every hour by the main computers.
- In the soil laboratory of the factory, the moisture rates of feeding materials are calculated regularly. Average moisture rate of each feeding material have been recorded by using a simple and accurate method. The weight of each substance entering the laboratory is measured, after that; the related material is heated in an oven for a certain time. When it get colds, the substance re-weighed to calculate the moisture rate precisely.
- The electricity consumption of the mill is read from the electricity panels and recorded by the mill operator assistants.

Energy, exergy and mass balances

1st and 2nd law analysis methodology is used for each component of the factory. The mass flow rates, specific heat capacities, temperature and pressure values of substances entering and leaving each factory units are calculated by using the equations below.

Table 1 Raw mill specifications

Model	Inside Diameter (mm)	Length (mm)	Rotate Speed (rev/min)	Ball Charge Capacity (tons)	Feeding Mine Granularity (mm)	Moisture Content of Feed and Discharge (%)	Fineness Residue 90 μm (%)	Processing Capacity (tons/h)	Power (kW)	Weight (tons)
Humboldt	4,400	14,000	15.9	125	≤35	15 – 1	12–14	160	3250	230

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

The mass balance:

The energy balance:

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

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

the heat transfer, power and mass flow rates are denoted by $\dot{Q}$, $\dot{W}$ and $\dot{m}$.

1st law efficiency:

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

The exergy balance:

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

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

The heat transfer rate at temperature T_p is denoted by $\dot{Q}_p$. P_0 and T_0 are used to define the thermodynamic properties at the dead state.

The flow exergy is:

$$\psi = (h - h_0) - T_0(s - s_0) \tag{7}$$

The exergy destruction:

$$\dot{E}x_{\text{dest}} = T_0 \dot{S}_{\text{gen}} \tag{8}$$

The entropy generation rate is designated by using $\dot{S}_{\text{gen}}$.

2nd law efficiency:

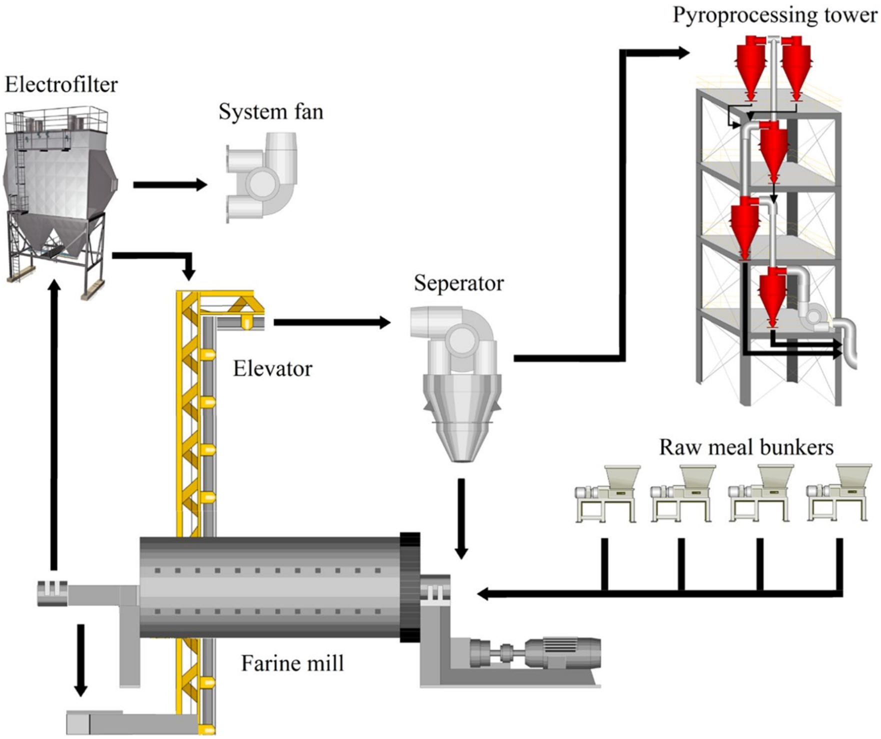
$$\eta_{II} = \frac{\sum \dot{E}x_{\text{out}}}{\sum \dot{E}x_{\text{in}}} \tag{9}$$

It is clear that, when the irreversibility of a system is decreased, the exergetic efficiency can be maximized. The energy sources and materials can be used in a best way by increasing the exergetic efficiency of a system.

The constant pressure and volume specific heat values are assumed equal for incompressible substances:

$$c_p = c_v = c \tag{10}$$

Fig. 2 Flow diagram of raw meal production and raw meal mill system



Internal energy and enthalpy change of any system are calculated by:

$$\Delta u = \int_1^2 c(T)dT = c_{\text{avg}}\left(T_2 - T_1\right) \tag{11}$$

$$\Delta h = \Delta u + v\Delta P \tag{12}$$

v and ΔP are used for specific volume and pressure change values.

The enthalpy values of substances:

$$\Delta h_{\text{in}} = c_{\text{avg}}\left(T_1 - T_0\right) \tag{13a}$$

$$\Delta h_{\text{out}} = c_{\text{avg}}\left(T_2 - T_0\right) \tag{13b}$$

The input and output temperatures of each substance entering and leaving each system are denoted by T_1 and T_2. Atmospheric temperature of the environment is expressed by using T_0.

Entropy change for liquids, solids (Eq. 14) and ideal gases (Eq. 15) are calculated by:

$$s_2 - s_1 = c_{avg}\ln\frac{T_2}{T_0} \tag{14}$$

$$s_2 - s_1 = c_{p,avg}\ln\frac{T_2}{T_0} - R\ln\frac{P_2}{P_0} \tag{15}$$

Δs of the input and output materials are:

$$\Delta s_{in} = c_{p,avg}\ln\frac{T_1}{T_0} \tag{16a}$$

$$\Delta s_{out} = c_{p,avg}\ln\frac{T_2}{T_0} \tag{16b}$$

The exergy values in the units:

$$\Delta\psi_{in} = \Delta h_{in} - T_0\Delta s_{in} \tag{17a}$$

$$\Delta\psi_{out} = \Delta h_{out} - T_0\Delta s_{out} \tag{17b}$$

Heat transfer rate between the surface of raw meal, cyclones of pyro-processing tower, rotary kiln and other units is found by using the Eqs. (18)-(23) (Fig. 3):

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

where R_{total} is the total thermal resistance of each unit,

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

The thermal resistance values for each heat transfer mechanism are calculated by using the following equations.

$$R_{conv} = \frac{1}{2\pi r_1 hL} \tag{20}$$

$$R_{cond} = \frac{\ln(r_2/r_1)}{2\pi kL} \tag{21}$$

$$R_{rad} = \frac{1}{h_{rad}A} \tag{22}$$

The convection and radiation heat transfer coefficients and the thermal conductivity values are denoted by h, k and h_{rad}, respectively. Equation (23) is used to calculate h_{rad}:

$$h_{rad} = \varepsilon\sigma(T^2_{out,surf} + T^2_{out})(T_{out,surf} + T_{out}) \tag{23}$$

where ε is the emissivity of the surface.

Exergoeconomic assessment methodology

Exergy analysis should be combined with the economic rules by using exergoeconomic methodologies providing the researchers to plan an efficient and cost effective unit. The annual values of carrying charges, material and fuel prices, and operating and maintenance (O&M) costs are the necessary information used in the economic analysis of systems.

Nevertheless, calculated present cost of any pattern may change in years, therefore during economic assessments, the levelized annual value is used (Hermann, 2006):

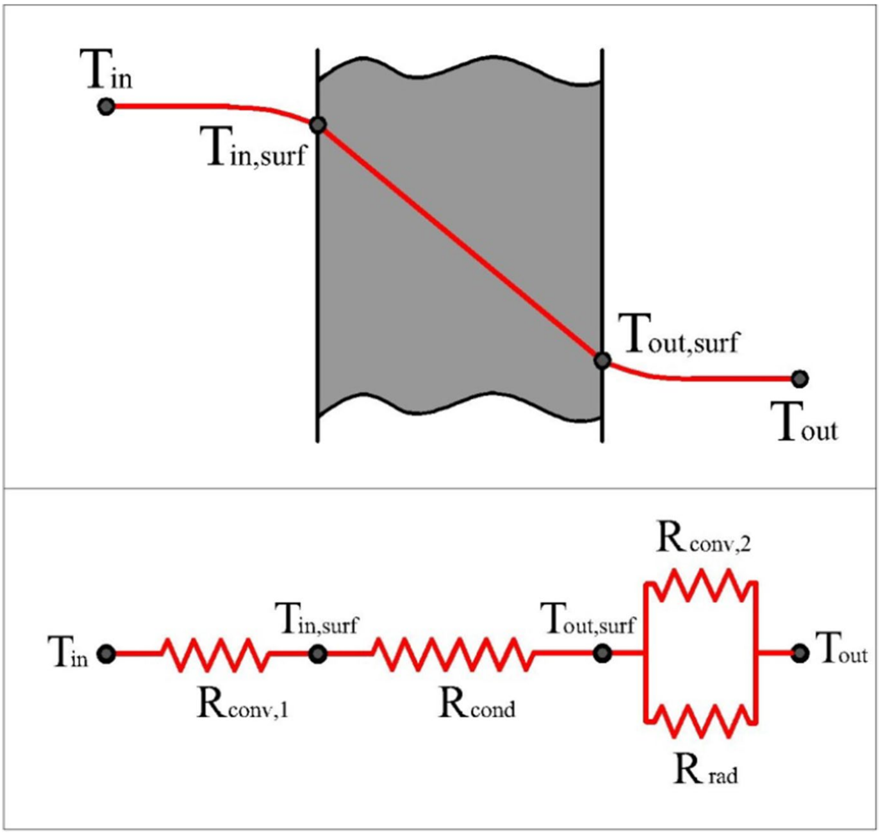


Fig. 3 Thermal resistance network for each component

$$A = CRF \sum_{m=1}^{n} P_m = \frac{i_{eff}(i_{eff}+1)^n}{(i_{eff}+1)^n - 1} \sum_{m=1}^{n} P_m \tag{24}$$

where

$$P_m = C_m \frac{1}{(i_{eff}+1)^m} \tag{25}$$

The rate of interest and payment period are denoted by i_{eff} and n.

The cost rate is calculated by using Eq. (26):

$$\dot{Z}_k = \left[\frac{CC_L + OMC_L}{\tau}\right] \frac{PEC_k}{\sum_k PEC_k} \tag{26}$$

The levelized cost rate of the fuel used in the units is:

$$\dot{C}_{EX} = \frac{EXC_L}{\tau} \tag{27}$$

The cost of each flow stream in the plant is calculated to see the cost form of each factory unit and the overall system (Xiang et al., 2004). To understand the cost structure of the cement factory, SPECO method is used in this comprehensive research.

Not only does this method help calculate the specific input and output exergies, it also allows determining costs per exergy unit and the secondary costing calculations for each unit of the factory.

In the first step, the exergy streams are determined, after that fuels and products of each unit are defined, finally required cost equations are completed.

In this method each exergy stream is associated with a cost, the equations used in calculations are indicated in Eqs. (28) to (31):

$$\dot{C}_i = c_i \dot{E}x_i = c_i(\dot{m}_i \psi_i) \tag{28}$$

$$\dot{C}_e = c_e \dot{E}x_e = c_e(\dot{m}_e \psi_e) \tag{29}$$

$$\dot{C}_w = c_w \dot{E}x_w \tag{30}$$

$$\dot{C}_q = c_q \dot{E}x_q \tag{31}$$

The exergoeconomic balance equation for each component of the facility, consuming electrical energy and loosing heat energy from its the mantle is written as:

$$\sum_i (c_i \dot{E}x_i) + c_w \dot{E}x_w + \dot{Z}_k = \sum_e (c_e \dot{E}x_e) + c_q \dot{E}x_q \tag{32}$$

In the exergoeconomic cost balance equations, all terms are positive and “a-1” auxiliary equations must be defined if there are “a” exergy flow leaving the unit.

In this study, F and P methodologies are used in SPECO approach to obtain auxiliary equations. F (fuel) rule is applied if the exiting exergy of a stream in a unit is defined as a fuel. The auxiliary equations are determined for each removed exergy of a unit. Exergetic cost balance is achieved by equalizing the exiting and entering exergetic costs of each stream from all units.

P rule expresses that each exergy flow in the product side has the same average cost to obtain one auxiliary equation for the related unit. The cost balance equations derived from F principle are used to calculate this cost.

Figure 4 presents an actual cement production facility. The mass, energy and exergy balances are indicated in Table 2. Table 3 shows the cost balances and supplementary equations.

Exergoeconomic performance parameters

In this study, the exergoeconomic factor f_k is used to describe the exergoeconomic performance of each component of the factory. In Eq. (33) the cost flow rates for each unit of the factory related to the exergy loss is considered.:

$$f_k = \frac{\dot{Z}_k}{\dot{Z}_k + c_{f,k} \dot{E}x_{D,k}} \tag{33}$$

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

The relative cost difference, r_k, is a very valuable parameter in exergoeconomic assessments. The relative increase in the cost per exergy unit between fuel (F) and product (P) of each unit of the factory is described by using r_k:

$$r_k = \frac{c_{p,k} - c_{f,k}}{c_{f,k}} \tag{34}$$

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

The cost rate of exergy destruction and ratio of exergy consumption rate of each unit to total capital cost parameters are expressed in Eqs. (35) and (36):

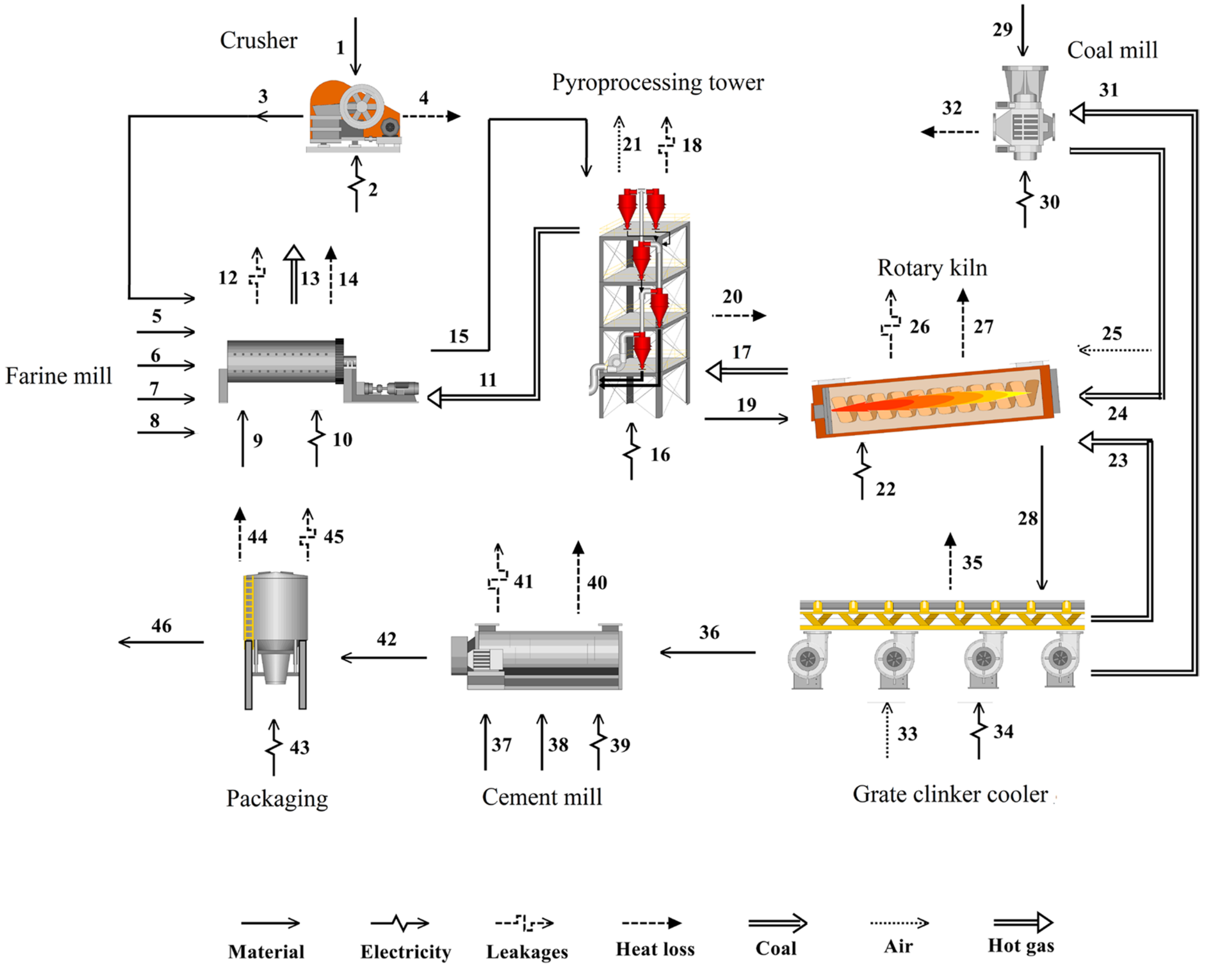


Fig. 4 Schematic of an actual cement factory (Atmaca & Yumrutaş, 2014)

$$\dot{D}_{D,k} = c_{f,k}\dot{E}x_{D,k} \tag{35}$$

$$Ex\Lambda = \frac{\dot{E}x_{C,k}}{TCI_{system}} \tag{36}$$

In cement industry, electricity and coal are the two main energy resources.

By using the real energy consumption and manufacturing (raw meal, clinker and cement) data, the SEC, SExC and MC values are calculated by using the Eqs. (37) to (41):

$$SEC = \frac{\dot{E}_{C,k}}{\dot{m}_{material}} \tag{37}$$

$$SExC = \frac{\dot{E}x_{C,k}}{\dot{m}_{material}} \tag{38}$$

$$MC_{farine} = \frac{\sum \dot{C}_{crusher} + \sum \dot{C}_{rawmill}}{\dot{m}_{farine}} \tag{39}$$

$$MC_{clinker} = \frac{\sum \dot{C}_{crusher} + \sum \dot{C}_{rawmill} + \sum \dot{C}_{pyro} + \sum \dot{C}_{rotary} + \sum \dot{C}_{coalmill} + \sum \dot{C}_{cooler}}{\dot{m}_{clinker}} \tag{40}$$

Table 2 Thermodynamic relations for the factory units

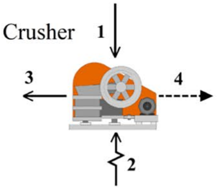
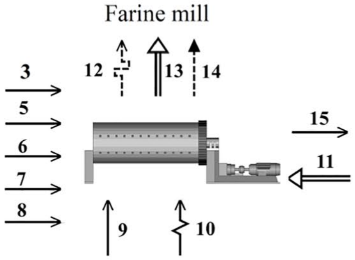
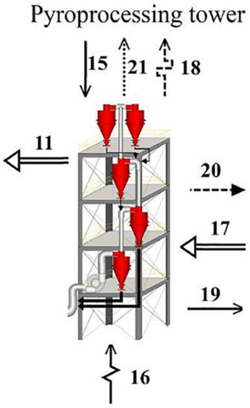
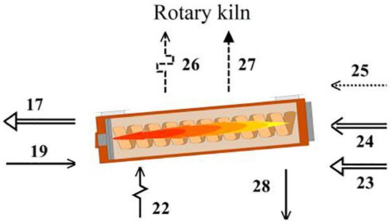
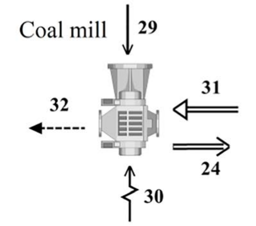
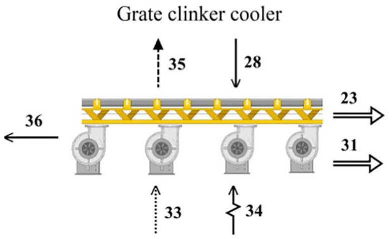
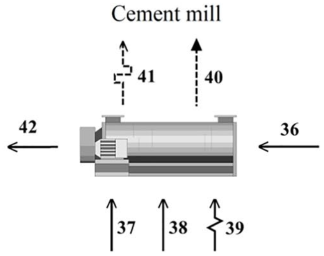
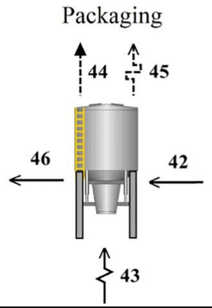
Components	**Mass, energetic and exergetic relations**
	$\dot{m}_1 = \dot{m}_3 = \dot{m}_{\lim estone}$ $\eta_I = \dfrac{\dot{E}_3}{\dot{E}_1 + \dot{E}_2}$ $\dot{E}_1 + \dot{E}_2 = \dot{E}_3 + \dot{E}_4$ $\dot{E}x_{dest} = (\dot{E}x_2 + \dot{E}x_1) - (\dot{E}x_3 + \dot{E}x_4)$ $\eta_{II} = \dfrac{\dot{E}x_3 + \dot{E}x_4}{\dot{E}x_1 + \dot{E}x_2}$
	$\dot{m}_3 + \dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 + \dot{m}_9 + \dot{m}_{11} = \dot{m}_{12} + \dot{m}_{13} + \dot{m}_{15}$ $\dot{m}_{11} = \dot{m}_{13} = \dot{m}_{hotgas}$ $\dot{E}_3 + \dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_{10} + \dot{E}_{11} = \dot{E}_{12} + \dot{E}_{13} + \dot{E}_{14} + \dot{E}_{15}$ $\dot{E}x_{dest} = (\dot{E}x_3 + \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_9 + \dot{E}x_{10} + \dot{E}x_{11})$ $- (\dot{E}x_{12} + \dot{E}x_{13} + \dot{E}x_{14} + Ex_{15})$ $\eta_I = \dfrac{\dot{E}_{12} + \dot{E}_{13} + \dot{E}_{15}}{\dot{E}_3 + \dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 + \dot{E}_9 + \dot{E}_{10} + \dot{E}_{11}}$ $\eta_{II} = \dfrac{\dot{E}x_{12} + \dot{E}x_{13} + \dot{E}x_{14} + \dot{E}x_{15}}{\dot{E}x_3 + \dot{E}x_5 + \dot{E}x_6 + \dot{E}x_7 + \dot{E}x_8 + \dot{E}x_9 + \dot{E}x_{10} + \dot{E}x_{11}}$
	$\dot{m}_{15} + \dot{m}_{17} = \dot{m}_{11} + \dot{m}_{18} + \dot{m}_{19} + \dot{m}_{21}$ $\dot{m}_{15} = \dot{m}_{18} + \dot{m}_{19} = \dot{m}_{farine}$ $\dot{m}_{17} = \dot{m}_{11} + \dot{m}_{21} = \dot{m}_{hotgas}$ $\dot{E}_{15} + \dot{E}_{16} + \dot{E}_{17} = \dot{E}_{11} + \dot{E}_{18} + \dot{E}_{19} + \dot{E}_{20} + \dot{E}_{21}$ $\dot{E}x_{dest} = (\dot{E}x_{15} + \dot{E}x_{16} + \dot{E}x_{17}) - (\dot{E}x_{11} + \dot{E}x_{18} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21})$ $\eta_I = \dfrac{\dot{E}_{11} + \dot{E}_{18} + \dot{E}_{19} + \dot{E}_{21}}{\dot{E}_{15} + \dot{E}_{16} + \dot{E}_{17}}$ $\eta_{II} = \dfrac{\dot{E}x_{11} + \dot{E}x_{18} + \dot{E}x_{19} + \dot{E}x_{20} + \dot{E}x_{21}}{\dot{E}x_{15} + \dot{E}x_{16} + \dot{E}x_{17}}$
	$\dot{m}_{19} + \dot{m}_{23} + \dot{m}_{24} + \dot{m}_{25} = \dot{m}_{17} + \dot{m}_{26} + \dot{m}_{28}$ $\dot{m}_{19} = 0.58 \text{ x } \dot{m}_{28} = \dot{m}_{farine-clin\,\mathrm{ker}}$ $\dot{E}_{19} + \dot{E}_{22} + \dot{E}_{23} + \dot{E}_{24} + \dot{E}_{25} = \dot{E}_{17} + \dot{E}_{26} + \dot{E}_{27} + \dot{E}_{28}$ $\dot{E}x_{dest} = (\dot{E}x_{19} + \dot{E}x_{22} + \dot{E}x_{23} + \dot{E}x_{24} + \dot{E}x_{25}) - (\dot{E}x_{17} + \dot{E}x_{26} + \dot{E}x_{27} + \dot{E}x_{27})$ $\eta_I = \dfrac{\dot{E}_{17} + \dot{E}_{26} + \dot{E}_{28}}{\dot{E}_{19} + \dot{E}_{22} + \dot{E}_{23} + \dot{E}_{24} + \dot{E}_{25}}$ $\eta_{II} = \dfrac{\dot{E}x_{17} + \dot{E}x_{26} + \dot{E}x_{27} + \dot{E}x_{28}}{\dot{E}x_{19} + \dot{E}x_{22} + \dot{E}x_{23} + \dot{E}x_{24} + \dot{E}x_{25}}$

Table 2 (continued)

	$\dot{m}_{29} = \dot{m}_{24} = \dot{m}_{coal}$ $\dot{E}_{29} + \dot{E}_{30} + \dot{E}_{31} = \dot{E}_{24} + \dot{E}_{32}$ $\dot{E}x_{dest} = (\dot{E}x_{29} + \dot{E}x_{30} + \dot{E}x_{31}) - (\dot{E}x_{24} + \dot{E}x_{32})$ $\eta_I = \frac{\dot{E}_{24}}{\dot{E}_{29} + \dot{E}_{30} + \dot{E}_{31}}$ $\eta_{II} = \frac{\dot{E}x_{24}}{\dot{E}x_{29} + \dot{E}x_{30} + \dot{E}_{31}}$
	$\dot{m}_{28} + \dot{m}_{33} = \dot{m}_{23} + \dot{m}_{35} = \dot{m}_{hot-cold,clin\,ker}$ $\dot{}_{28} + \dot{}_{33} + \dot{}_{34} = \dot{}_{23} + \dot{}_{31} + \dot{}_{35} + \dot{}_{36}$ $\dot{E}x_{dest} = (\dot{E}x_{28} + \dot{E}x_{33} + \dot{E}x_{34}) - (\dot{E}x_{23} + \dot{E}x_{31} + \dot{E}x_{35} + \dot{E}x_{36})$ $\eta_I = \frac{\dot{E}_{23} + \dot{E}_{31} + \dot{E}_{36}}{\dot{E}_{28} + \dot{E}_{33} + \dot{E}_{34}}$ $\eta_{II} = \frac{\dot{E}x_{23} + \dot{E}x_{31} + \dot{E}x_{36}}{\dot{E}x_{28} + \dot{E}x_{33} + \dot{E}x_{34}}$
	$\dot{m}_{35} + \dot{m}_{36} + \dot{m}_{37} = \dot{m}_{40} + \dot{m}_{41}$ $\dot{E}_{35} + \dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38} = \dot{E}_{39} + \dot{E}_{40} + \dot{E}_{41}$ $\dot{E}x_{dest} = (\dot{E}x_{35} + \dot{E}x_{36} + \dot{E}x_{37} + \dot{E}x_{38}) - (\dot{E}x_{39} + \dot{E}x_{40} + \dot{E}x_{41})$ $\eta_I = \frac{\dot{E}_{41} + \dot{E}_{42}}{\dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38} + \dot{E}_{39}}$ $\eta_{II} = \frac{\dot{E}x_{40} + \dot{E}x_{41} + \dot{E}x_{42}}{\dot{E}x_{36} + \dot{E}x_{37} + \dot{E}x_{38} + \dot{E}x_{39}}$
	$\dot{m}_{42} = \dot{m}_{46} = \dot{m}_{cement}$ $\dot{E}_{42} + \dot{E}_{43} = \dot{E}_{44} + \dot{E}_{45} + \dot{E}_{46}$ $\dot{E}x_{dest} = (\dot{E}x_{42} + \dot{E}x_{43}) - (\dot{E}x_{44} + \dot{E}x_{45} + \dot{E}x_{46})$ $\eta_I = \frac{\dot{E}_{45} + \dot{E}_{46}}{\dot{E}_{42} + \dot{E}_{43}}$ $\eta_{II} = \frac{\dot{E}x_{44} + \dot{E}x_{45} + \dot{E}x_{46}}{\dot{E}x_{42} + \dot{E}x_{43}}$

$$MC_{cement} = \frac{\sum \dot{C}_{total}}{\dot{m}_{cement}} \tag{41}$$

Results and discussions

The overall results are presented by performing thermodynamic and exergoeconomic analysis in Sects. "Thermodynamic analysis" and "Exergoeconomic analysis" respectively. The effects of moisture content of raw meal and hot gas supply to the raw mill unit on the overall plant performance are presented in Sect. "The effects of moisture content and hot gas supply on overall thermodynamic and exergoeconomic parameters of the factory.".

Thermodynamic analysis

Based on the state number defined in Fig. 4., Table 5 presents the energetic and exergetic parameters for the whole factory. The exergetic definitions for fuels ($\dot{E}_F$) and products ($\dot{E}_P$) are defined for each component of the cement factory.

Table 3 SPECO equations for each component of the factory

Components	SPECO equations	Auxiliary equations
Crusher	$\dot{C}_{W,Crusher} + \dot{Z}_{Crusher} + \dot{C}_1 = \dot{C}_3 + \dot{C}_{Q,4}$	$c_1 = c_3$
Raw mill	$\dot{C}_{W,Rawmill} + \dot{Z}_{Rawmill} + \dot{C}_3 + \dot{C}_5 + \dot{C}_6 + \dot{C}_7 + \dot{C}_8$ $+\dot{C}_9 + \dot{C}_{11} = \dot{C}_{12} + \dot{C}_{13} + \dot{C}_{Q,14} + \dot{C}_{15}$	$c_{11} = c_{13}$ $c_3 = c_5 = c_6 = c_7 = c_8 = c_9 = c_{12}$ $\frac{\dot{C}_{13}}{\dot{E}x_{13}} = \frac{\dot{C}_{11}}{\dot{E}x_{11}}$ (F)
Pyro-processing tower	$\dot{C}_{W,Pyro} + \dot{Z}_{Pyro} + \dot{C}_{15} + \dot{C}_{17}$ $= \dot{C}_{11} + \dot{C}_{18} + \dot{C}_{19} + \dot{C}_{Q,20} + \dot{C}_{21}$	$c_{21} = 0$ $c_{17} = c_{11}$ $c_{15} = c_{18}$ $\frac{\dot{C}_{15}}{\dot{E}x_{15}} = \frac{\dot{C}_{19}}{\dot{E}x_{19}}$ (P) $\frac{\dot{C}_{17}}{\dot{E}x_{17}} = \frac{\dot{C}_{11}}{\dot{E}x_{11}}$ (F)
Coal mill	$\dot{C}_{W,Coalmill} + \dot{Z}_{Coalmill} + \dot{C}_{29} + \dot{C}_{31} = \dot{C}_{24} + \dot{C}_{Q,32}$	$\frac{\dot{C}_{29}}{\dot{E}x_{29}} = \frac{\dot{C}_{24}}{\dot{E}x_{24}}$ (P)
Rotary kiln	$\dot{C}_{W,Rotary} + \dot{Z}_{Rotary} + \dot{C}_{19} + \dot{C}_{23} + \dot{C}_{24} + \dot{C}_{25}$ $= \dot{C}_{17} + \dot{C}_{26} + \dot{C}_{Q,27} + \dot{C}_{28}$	$c_{25} = 0$ $c_{17} = c_{23}$ $\frac{\dot{C}_{19}}{\dot{E}x_{19}} = \frac{\dot{C}_{28}}{\dot{E}x_{28}}$ (P) $\frac{\dot{C}_{24}}{\dot{E}x_{24}} = \frac{\dot{C}_{17}}{\dot{E}x_{17}}$ (F)
Grate clinker cooler	$\dot{C}_{W,Cooler} + \dot{Z}_{Cooler} + \dot{C}_{28} + \dot{C}_{33}$ $= \dot{C}_{23} + \dot{C}_{31} + \dot{C}_{Q,35} + \dot{C}_{36}$	$c_{33} = 0$ $c_{36} = c_{28}$ $\frac{\dot{C}_{28}}{\dot{E}x_{28}} = \frac{\dot{C}_{36}}{\dot{E}x_{36}}$ (P)
Cement mill	$\dot{C}_{W,Cementmill} + \dot{Z}_{Cementmill} + \dot{C}_{36} + \dot{C}_{37} + \dot{C}_{38}$ $= \dot{C}_{Q,40} + \dot{C}_{41} + \dot{C}_{42}$	$c_{37} = c_{38} = c_{41}$
Packaging unit	$\dot{C}_{W,Packaging} + \dot{Z}_{Packaging} + \dot{C}_{42} = \dot{C}_{Q,44} + \dot{C}_{45} + \dot{C}_{46}$	$\frac{\dot{C}_{42}}{\dot{E}x_{42}} = \frac{\dot{C}_{46}}{\dot{E}x_{46}}$ (P) $c_{42} = c_{45} = c_{46}$

Table 4 Properties of each stream in the factory

No	Stream	$\dot{m}$[1] (kg/s)	T[2] (K)	$\dot{E}$[3] (kW)	$\dot{E}x$[4] (kW)
1	Input limestone	15.07	305.00	61.79	0.51
2	Crusher electrical power	–	–	250.00	250.00
3	Fine limestone	15.07	322.00	271.86	9.51
4	Crusher boundary heat loss	–	–	171.66	171.66
5	Marl	12.00	295.00	38.41	0.33
6	Clay	4.13	295.00	18.98	0.16
7	Iron ore	0.38	295.00	1.16	0.01
8	Bauxite	0.38	295.00	1.20	0.01
9	Moisture	4.17	295.00	87.25	0.74
10	Electrical power (raw meal mill)	–	–	2,000.00	2,000.00
11	Waste hot gas (pyro-processing tower)	18.43	560.00	7,215.13	2,115.47
12	Air leakages	1.13	295.00	5.69	0.05
13	Hot gas exhaust	18.43	385.00	2,538.66	342.72
14	Heat loss (raw meal mill)	–	–	2,842.11	2,842.11
15	Raw mix (raw meal)	40.06	385.00	3,729.77	503.51
16	The electrical power of the tower	–	–	5,000.00	5,000.00
17	Hot gas supplied from the burner	18.43	1,725.00	40,836.29	25,798.22
18	Air leakages	7.01	300.00	0.00	0.00
19	Hot raw meal	28.74	1,011.00	20,638.80	10,058.91
20	Heat loss (Pyro-processing tower)	–	–	22,906.71	22,906.71
21	Exhaust	18.43	227.46	4,191.96	1,057.58
22	Rotary kiln electrical power	–	–	4,341.50	4,341.50
23	Secondary air (grate clinker cooler)	24.86	1,083.91	23,240.13	12,047.60
24	Coal	2.00	344.00	112.60	9.34
25	Primary air	2.74	290.00	87.48	4.24
26	Air leakages	3.58	710.00	1,581.00	603.56
27	Heat loss (rotary burner)	–	–	12,542.51	12,542.51
28	Hot clinker	18.11	1,550.00	24,293.94	14,921.93
29	Coarse coal	2.00	305.00	11	0.09
30	Electrical power (coal mill)	–	–	1,504	1,504
31	Hot gas (grate clinker cooler)	4.97	707.00	2,428.73	894.07
32	Heat loss (coal mill)	–	–	2,670.36	2,670.36
33	Fresh air	47.17	313.00	607.04	12.78
34	Electrical power (grate clinker cooler)	–	–	1,873.00	1,873.00
35	Heat loss (grate clinker cooler)	–	–	4,510.07	4,510.07
36	Clinker (calcinated and cooled)	17.78	390.00	1,408.37	176.68
37	Gypsum	0.92	310.00	7.56	0.12
38	Limestone	0.99	310.00	7.30	0.12
39	Electrical power (cement mill)	–	–	2,202	2,202
40	Heat loss (Cement mill)	–	–	538.67	538.67
41	Air leakages	1.14	381.00	93.43	10.72
42	Cement	20.89	381.00	1,725.60	198.02
43	Electrical power (packaging unit)	–	–	152	152
44	Heat loss (packaging unit)	–	–	152.01	152.01
45	Air leakages	0.10	310.00	1.01	0.02
46	Finished cement	20.79	310.00	212.02	3.46

[1] Mass flow rate

[2] Temperature

[3] Energy rate

[4] Exergy rate

Table 5 Energy and exergy rates and 1st and 2nd law efficiencies of the factory units

Units	$\dot{E}_{in}$ (kW)	$\dot{E}x_{in}$ (kW)	$\dot{E}_{out}$ (kW)	$\dot{E}x_{out}$ (kW)	$\dot{E}_{L}$ (kW)	$\dot{E}x_{L}$ (kW)	μ_I (%)	μ_{II} (%)
Crusher	311.79	250.51	210.08	5.74	101.71	244.77	67.38	2.29
Raw mill	10,015.80	4,208.49	7,173.69	968.44	2,842.11	3,240.05	71.62	23.01
Pyro-processing tower	47,737.48	30,951.22	24,830.76	11,116.49	22,906.71	19,834.73	52.02	35.92
Rotary kiln	111,182.83	89,497.43	62,102.68	34,649.86	49,080.15	54,847.57	55.86	38.72
Coal mill	3,943.73	2,398.16	1,273.37	263.45	2,670.36	2,134.71	32.29	10.99
Grate clinker cooler	30,336.92	19,078.36	25,826.85	11,443.26	4,510.07	7,635.10	85.13	59.98
Cement mill	2,357.70	2,204.54	1,819.03	208.74	538.67	1,995.80	77.15	9.47
Packaging	365.04	155.47	213.03	3.47	152.01	152.00	58.36	2.23
Total	206,251.28	148,744.19	123,449.49	58,659.45	82,801.79	90,084.74	59.85*	39.44**

* 1st law efficiency of entire factory

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

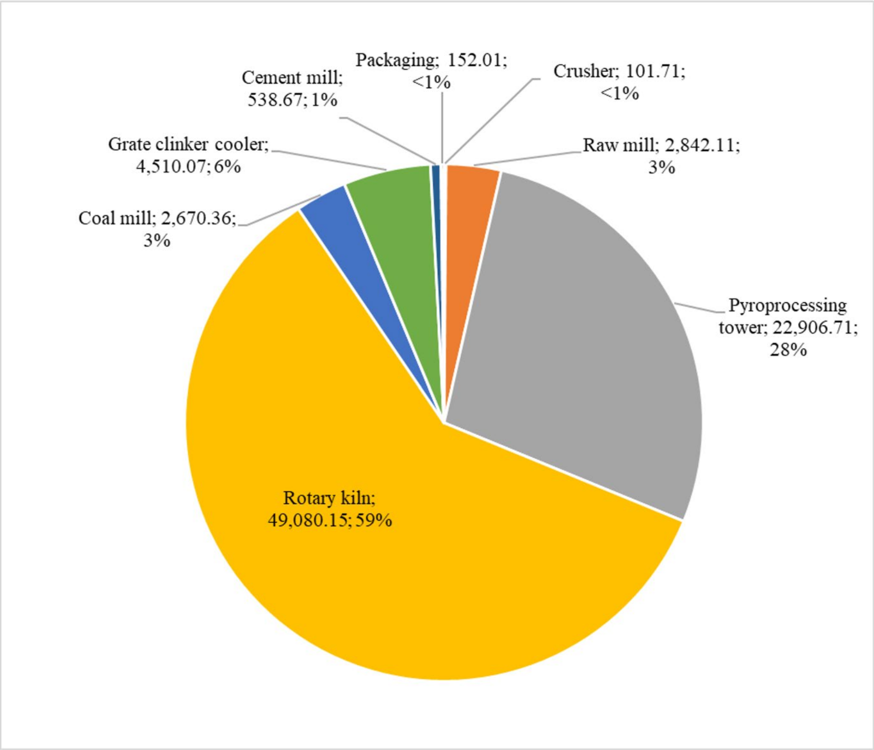
Lignite coal is the common fuel used in dry type cement manufacturing facilities.

In order to calculate the chemical exergy of a carbon-based fuel (coal that contains C, S, N, O, H and halogens) Gibbs free energy relations are used with empirical data.

It is assumed that, the fuel entropy is equal to the total entropies of the fundamental constituents. The chemical exergy (MJ/kg) of the coal is calculated by Eq. (42) (Silveira & Tuna, 2003).

$$\begin{aligned}\psi_{fuel} =& 32.90[C] + 2.040[N] + 117.7[H] \\ & + 16.34[S] - 13.41[O] - T_0[ash]s^0_{ash} \\ & + 0.15[O][32.83[C] + 19.50[S] \\ & + 141.9([H] - [O]/8)]\end{aligned} \tag{42}$$

Fig. 5 The rate of energy loss in factory units (kW)



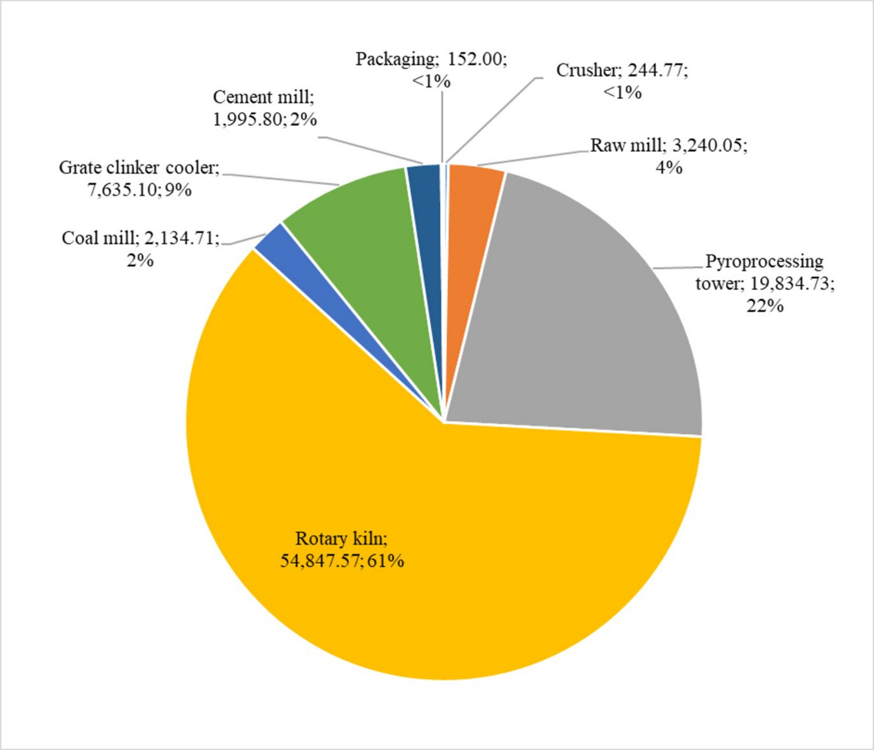


Fig. 6 The rate of exergy loss in factory units (kW)

Mass fractions of the constituents are denoted by *C, N, H, S* and *O* (Brouwers & Eijk, 2002).

With the help of the equations presented in Table 2 and 3, energy and exergy input/output rates, losses, efficiencies, the ratio of energy and exergy losses to total capital cost are evaluated by using Eqs. (35) through (44) and presented in Tables 4 and 5. The rates of losses in the units of the factory are presented in Figs. 5 and 6 respectively.

We reached the following results:

- The overall 1st and 2nd law performances of the cement factory are evaluated to be 59.85% and 39.44%.
- The 1st law efficiencies of the crusher, raw meal, pyro-processing tower, burner, coal mill, cooler, cement grinding unit and packaging system are calculated to be 67.38%, 71.62%, 52.02%,

Table 6 The cost rates for each unit of the factory

Unit	PEC ($)	$\dot{Z}_k^{CI}$($/h)	$\dot{Z}^{OM}{}_k$($/h)	$\dot{Z}_k^{T}$($/h)
Crusher	5,593,750	153.56	50.67	204.23
Raw mill	15,947,916	318.97	105.26	424.23
Pyroprocessing tower	17,864,583	305.01	100.65	405.66
Rotary kiln	20,156,250	344.13	113.56	457.69
Coal mill	8,093,750	188.86	62.32	251.18
Grate clinker cooler	5,187,500	88.57	29.23	117.79
Cement mill	16,281,250	325.63	107.46	433.09
Packaging	5,875,000	137.09	45.24	182.33
Installation, engineering, supervision, and unexpected costs	28,000,000			
TCI	123 M$	1861.81	614.4	2476.21

55.86%, 32.29%, 85.13%, 77.15% and 58.36% respectively.

- 176.68 GJ of energy is lost each hour in the rotary kiln.
- The energetic improvement potential and the ratio of energy losses to capital cost of the burner are found to be 21,665.76 kW and 274.24 kW/M$.
- The 2nd law efficiencies of the crusher, raw meal system, pyro-processing tower, rotary burner, coal mill, cooler, cement mill and packaging units are calculated to be 2.29%, 23.01%, 35.92%, 38.72%, 10.99%, 59.98%, 9.47% and 2.23% respectively.
- Because of the irreversible calcination process and tremendous heat losses, the rotary burner has the highest exergy loss rate (54.85 MW).
- Rotary burner and pyro-processing tower destructs around 60.88% and 22.02% of exergy input respectively. Pre-calcination of raw meal and clinker production are responsible for the destruction of 82.9% of total exergy of the factory.

Exergoeconomic analysis

The economic data of all units and other related expenses are obtained from the related departments of the factory. In order to escalate the calculated costs, nominal escalation rate of the related expenditures are determined.

Economic calculations contain the fuel cost, levelized costs per hour of capital investment cost, the purchased equipment cost (PEC), O&M cost and the total cost of the factory.

The total capital investment (TCI), O&M costs per year (OM), the total hours that the factory operate in a year (s), the rate of interest (i), the salvage value ratio (l) and system life time (n) are 123.6 M$, 5 M$, 8000 h, 8%, 16% and 50 year, respectively.

The detailed cost rates (PEC, $\dot{Z}_k^{CI}$, $\dot{Z}_k^{OM}$ and $\dot{Z}_k^{T}$) for each unit of the factory are presented in Table 6.

The economic data of the factory and the formulations given in Eqns. (24) through (27) are used to perform levelizaiton for the economic life of the factory. The exergy transfer rates (matter, power, heat transfer) for each state are calculated by using Eqs. (27)– (30). The results of Table 3 are presented in Table 7.

Table 7 The exergy and costs related to each exergetic flow

State	$\dot{E}x$ (kW)	$\dot{C}$ ($/h)	c ($/GJ)
1	0.701	0.0031	1.33
2	459.1	61.983	37.6
3	13.01	0.0622	1.31
4	171.6	7.612	12.3
5	0.331	0.0021	1.33
6	0.161	0.0011	1.33
7	0.0112	0.000053	1.33
8	0.0112	0.000053	1.33
9	0.741	0.0043	1.33
10	3250	438.75	37.6
11	2206.2	122.68	15.4
12	0.05	0.00022	1.33
13	310.4	17.25	15.45
14	4438.7	196.55	12.3
15	487.4	2.9	1.65
16	5000	675	37.5
17	25798.2	1433.721	15.45
18	0	0	0
19	10,058.9	59.780	1.65
20	22790.3	1009	12.3
21	1057.5	0	0
22	4341.5	586.1	37.5
23	12047.6	669.6	15.4
24	9.34	0.246	7.32
25	4.24	0	0
26	603.56	5.96	2.74
27	12542.5	555.4	12.3
28	14921.93	147.000	2.74
29	0.092	0.0022	7.32
30	1504	203.040	37.5
31	894.07	0	0
32	2670.36	118.200	12.3
33	12.78	0	0
34	1873.00	252.855	37.5
35	4510.07	199.703	12.3
36	176.68	1.740	2.74
37	0.12	0.001	1.32
38	0.12	0.001	1.32
39	2202	297.27	37.5
40	538.67	23.85	12.3
41	10.72	0.051	1.32
42	198.02	2.74	3.84
43	152	20.52	37.5
44	152.01	6.73	12.3
45	0.02	0.00022	3.84
46	3.46	0.048	3.84

Table 8 Exergoeconomic parameters for each unit of the factory

Component	$c_{f,k}$ (\$/GJ)	$c_{p,k}$ (\$/GJ)	ExΛ (kW/\$M*)	$\dot{Z}_k^T$ (\$/h)	$\dot{D}_{D,k}$ (\$/h)	r (%)	f (%)
Crusher system	37.50	13.62	1.22	204.23	33.04	63.67	86.07
Raw meal grinding system	40.59	13.95	16.20	424.23	473.43	65.63	47.26
Pyro-processing tower	43.67	29.39	99.17	405.66	3118.61	32.70	11.51
Rotary burner	44.82	30.47	274.24	457.69	8848.86	32.00	4.92
Coal grinding system	44.82	19.61	10.67	251.18	344.46	56.25	42.17
Grate clinker cooler	40.24	18.18	38.18	117.79	1105.95	54.83	9.63
Cement grinding system	40.24	17.46	9.98	433.09	289.09	56.60	59.97
Packaging system	41.34	19.98	0.76	182.33	22.62	51.68	88.96

* \$M: 1 million USA dollars

Fig. 7 The relative cost differences and exergy loss rates of each component of the factory

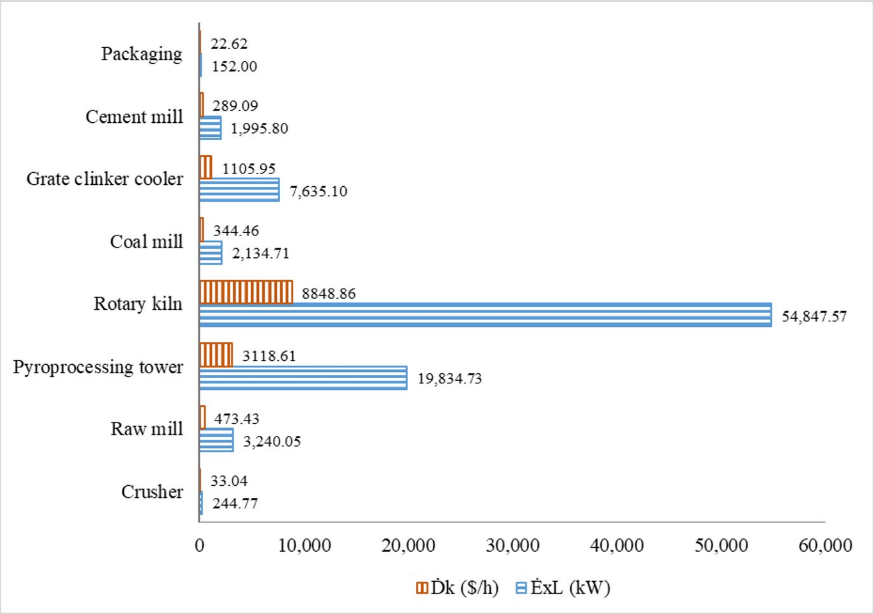


Table 9 SEC, SExC, MC and SPECO of cement factory

Product	$\dot{m}$ (kg/s)	$\dot{E}_{in}$ (kW)	$\dot{E}x_{in}$ (kW)	SEC (MJ/ton)	SExC (MJ/ton)	MC (\$/ton)	SPECO (\$/GJ)
Raw meal	40.06	2,943.82	3,484.83	73.48	86.99	4.13	50.52
Clinker	18.11	82,111.11	87,936.94	4,533.74	4,855.41	33.11	126.41
Cement	20.89	82,801.79	90,084.74	3,964.46	4,313.16	41.84	170.55

Table 10 Moisture rate of feeding materials

Raw meal mill feeding materials	Moisture (%) maximum – minimum
Limestone	8 – 2
Marl	18 – 4
Clay	17 – 4
Iron Ore	10 – 3
Bauxite	10 – 3

The exergetic cost of each stream of fuel ($c_{f,k}$) and product ($c_{p,k}$) the relation of exergy consumption rate to total capital cost (ExΛ) of each unit, the cost rate of total investment ($\dot{Z}_k^T$) and exergy destruction ($\dot{D}_{D,k}$), relative exergetic cost difference (r) and exergoeconomic factor (f) for each unit of the factory are calculated using Eqs. (33) through (36) and given in Table 8. Figure 7 presents the exergy loss rates and the relative cost differences of each component of the cement factory.

The following results are obtained:

- The cost rate and the exergetic cost of the fuel are found to be 864 \$/h and 3.84 \$/GJ, respectively.
- $\dot{Z}_k^{CI}$, $\dot{Z}_k^{OM}$ and $\dot{Z}_k^T$ of the factory is calculated to be 1861.81, 614.4, and 2467.21 \$/h, respectively.
- The packaging and crusher units have higher exergoeconomic factors (88.96% and 86.07%, respectively). That means, $\dot{Z}_k^T$ and $\dot{Z}_k^{OM}$ costs for these components should be decreased to increase the overall cost performance of the factory.
- The SPECO of the rotary burner is found to be 50.52 \$/GJ. The f value of the burner is 4.92%, that is relatively low compared to the other factory units. The exergoeconomic factor for raw meal and cement mills are 38.48% and 59.97% respectively.
- Total investment and destruction cost rates must be decreased in order to increase the exergoeconomic potential of the factory during pre-calcination of raw meal in pyro-processing tower and calcination processes in rotary burner.
- The exergetic destruction in pyro-processing unit and rotary kiln are found to be 54.85 and 19.83 MW. Reducing exergy destructions especially in these two plant components will increase the cost effectiveness dramatically.
- The exergoeconomic factor of raw meal mill 47.26%. This is the fifth lowest value among the factory units because of the high value of the exergetic destruction cost rate associated with the low investment values.
- The burner, pyro-processing system and grate cooler have the major exergetic loss rates and lowest exergoeconomic factors.

Table 9 shows SEC, SExC, MC and SPECO values for each product.

The effects of moisture content and hot gas supply on overall thermodynamic and exergoeconomic parameters of the factory.

There are many different ways to improve the performance of the grinding processes in cement

Table 11 The change of the performance parameters after a reduction of 50% of moisture content of input materials

Factory Units	$\dot{E}x_L$ (kW)	μ_I (%)	μ_{II} (%)	D (\$/h)	r (%)	f (%)
Crusher	244.18	73.50	2.53	31.99	62.57	86.46
Raw mill	3,166.88	72.26	23.35	450.08	64.67	48.52
Pyroprocessing tower	19,234.73	52.68	36.63	3,024.27	32.70	11.83
Rotary kiln	54,742.10	56.06	38.90	8,831.85	32.00	4.93
Coal mill	2,134.71	32.29	10.99	344.46	56.25	42.17
Grate clinker cooler	7,635.10	85.13	59.98	1,105.95	54.83	9.63
Cement mill	1,992.77	77.58	9.52	288.65	56.60	60.01
Packaging	152.02	58.18	2.23	22.63	51.68	88.96
Total	89,302.49	60.17*	39.73**	14,099.87		

* 1st law efficiency of entire factory

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

Table 12 SEC, SExC, MC and SPECO of cement factory after reducing the moisture content of raw materials

Material	SEC (MJ/ton)	SExC (MJ/ton)	MC ($/ton)	SPECO ($/GJ)
Raw meal	65.86	80.14	3.97	48.30
Clinker	4,423.83	4,746.86	32.46	124.19
Cement	3,901.12	4,253.31	41.45	168.33

factories. For an ideal grinding in a cement factory, the size of the raw materials, environmental conditions, the shape and size of the mill, feed material size, and moisture rate of feeding substances must be evaluated in detail. In this paper, the effects of hot gas supply and the moisture content of raw mill input materials has been assessed in detail.

The effects of moisture rate of feeding materials

Moisture rates of the feeding materials are measured regularly during 24 months of period. The moisture rates for each material are presented in Table 10.

With a typical moisture rate of 10% for the feeding products, the 1st (μ_I) and 2nd law (μ_{II}) efficiencies (Table 5), $\dot{D}_{D,k}$, r, f for the plant components (Table 8) and SEC, SExC and MC values (Table 9) for raw meal, clinker and cement are calculated and presented in previous sections of this study.

The exergy destructions, 1st and 2nd law efficiencies, $\dot{D}_{D,k}$, r and f for the plant components are presented in Table 11. When the moisture rate of the mill has been decreased by 50%, total exergy destruction of the factory has been decreased by 782.25 kW and the overall 1st and 2nd law efficiency values are increased by 0.52% and 0.75%.

Storing the raw meal mill input materials (Limestone, marl, clay, iron ore and bauxite) in a stock-hole is an effective way to decrease the moisture rate of feeding materials significantly. The application of waste hot gas supply from pyro-processing tower or the burner will help reduce moisture rates significantly. The experiments on site showed that raw meal production increases by reducing the moisture rate of input substances.

Besides the SEC and SExC values, the MC for raw meal, clinker and cement has been decreased by 3.75%, 1.96% and 0.93% respectively (Table 12).

Table 13 The change of the performance parameters after hot gas supply to the milling system*

Factory Units	$\dot{E}x_L$ (kW)	μ_I (%)	μ_{II} (%)	D ($/h)	r (%)	f (%)
Crusher	244.05	73.50	2.86	29.29	59.13	87.46
Raw mill	3,109.15	77.08	25.15	454.31	65.63	48.29
Pyroprocessing tower	18,541.28	53.90	37.65	2,822.53	30.49	12.57
Rotary kiln	54,494.54	56.52	39.31	8,519.43	29.83	5.10
Coal mill	2,134.71	32.29	10.99	344.46	56.25	42.17
Grate clinker cooler	7,635.10	85.13	59.98	1,105.95	54.83	9.63
Cement mill	1,890.84	78.11	10.07	264.43	55.05	62.09
Packaging	152.05	57.85	2.23	22.63	51.68	88.96
Total	88,201.72	60.96**	40.27***	13,563.04		

* 40 tons/h of hot gas with a temperature of 580 K has been supplied to the system by using the waste streams from pyro-processing tower

** 1st law efficiency of entire factory

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

Table 14 SEC, SExC, MC and SPECO of cement factory after hot gas supply to the system

Material	SEC (MJ/ton)	SExC (MJ/ton)	MCost ($/ton)	SPECO ($/GJ)
Raw meal	49.84	70.92	3.47	46.35
Clinker	4,202.93	4,557.33	31.03	119.47
Cement	3,779.77	4,160.46	40.47	162.22

Hot gas supply to the raw meal mill from the kiln and pyro-processing tower.

Hot gas should be supplied to the raw meal mill by collecting the waste streams from pyro-processing tower and rotary burner units. Hot gas supply rises the grinding efficiency, decreases the moisture rate of input substances, duration of grinding and SEC, that improves the 1st and 2nd law efficiency values significantly. The mass flow rate of the hot gas supplied to the system is 40 tons/h with a temperature of 580 K (Table 13).

The SExC values of raw meal, clinker and cement have been decreased by 8.25%, 5.49% and 4.89% respectively. By supplying hot gas to the milling system the raw meal manufacturing cost has been decreased by 15.81% to 3.47 $/ton of raw meal (Table 14).

The overall effects of hot gas supply and moisture rate reduction on the specific energy and exergy consumptions and costs of products are presented in Figs. 8, 9 and 10. Table 15 shows the change of specific exergy costs for the products after the applications (Fig. 11).

Conclusions

In this comprehensive research, the thermodynamic and exergoeconomic formulations are implemented to a currently running cement production factory using real factory data. The effects of milling system on the overall performance parameters of the factory have been investigated in detail. The outcomes of the study provide significant information regarding energetic and exergetic performance of the factory. The following main conclusions are drawn from the research:

- Milling and burning processes are the two key aspects for the cement factories and special considerations must be addressed to rise the energetic, exergetic and exergoeconomic performance of the entire factory.
- Controlling and decreasing the moisture content of raw meal used in raw meal mill by 50% and supplying the system hot gas from the pyro-processing tower have increased the overall efficiencies of the factory.
- The applications reduced the specific cost of cement production to 40.47 $/ton corresponding to a saving of 2,020,808 $/year.

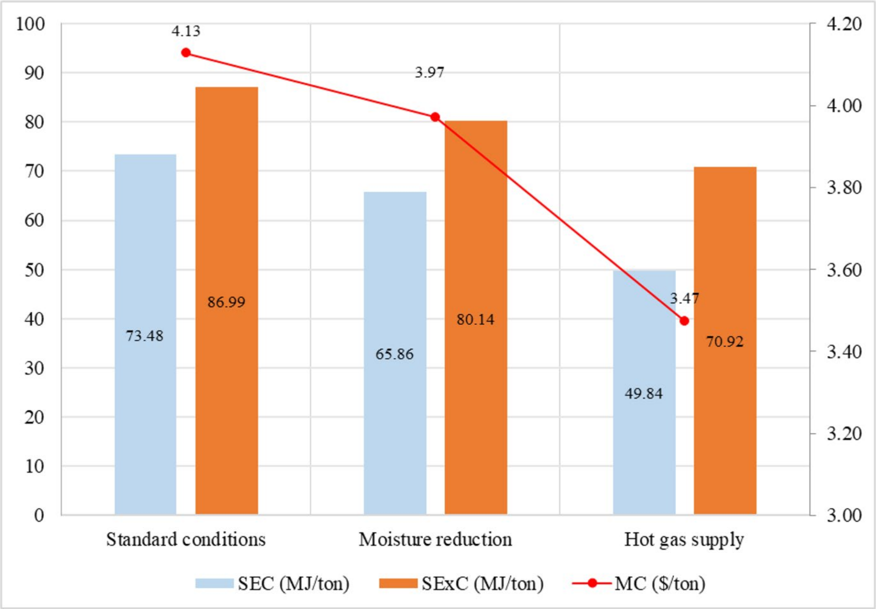


Fig. 8 The effects of hot gas supply and moisture rate reduction on the performance parameters of raw meal production

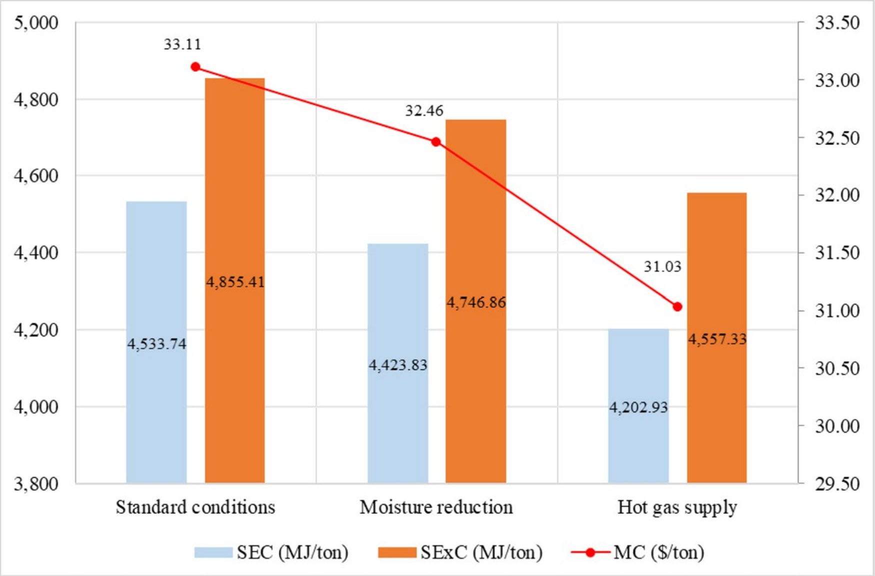


Fig. 9 The effects of hot gas supply and moisture rate reduction on the performance parameters of clinker production

- The *f* parameter of the kiln is comparatively low compared to the other factory units. The results showed that the combustion efficiency has important effect on the overall system efficiency.
- Exergetic performance results (Figs. 6 and 7) show that the rotary burner is the most energy and exergy destructive unit in the factory. The performance of the factory should be improved by achieving minor improvements in the kiln system.
- The collected data during the research showed that the hot gas supplied from the pyro-processing tower and rotary burner increases the raw meal production significantly (from 140 ton/h up to 170 ton/h).
- The moisture rate of feeding materials supplied to the grinding systems should be as low as possible to increase the performance of the factory, which effects the manufacturing process considerably.

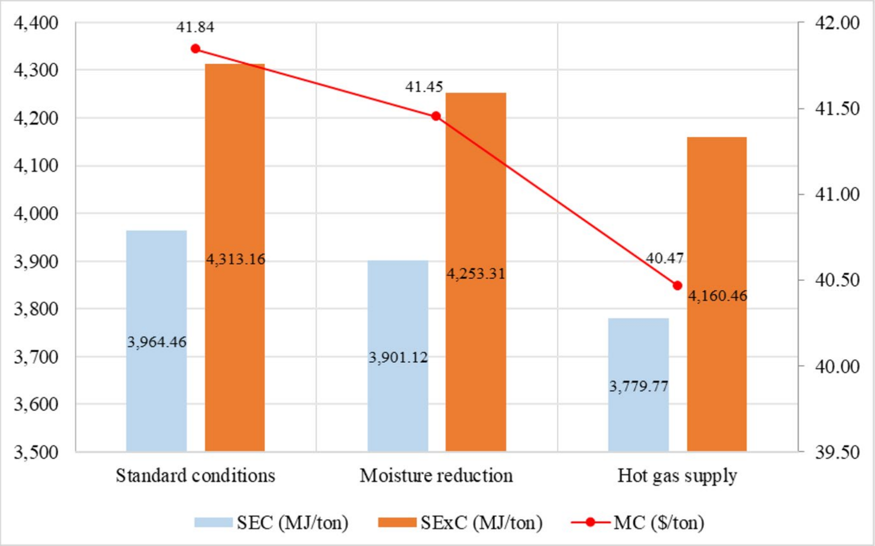


Fig. 10 The overall effects of hot gas supply and moisture rate reduction on the performance parameters of cement production

Table 15 The change of specific exergy costs for raw meal, clinker and cement

SPECO ($/GJ)	Standard conditions	Moisture reduction	Hot gas supply
Raw meal	50.52	48.30	46.35
Clinker	126.41	124.19	119.47
Cement	170.55	168.33	162.22

- The raw meal used in raw meal mills should be kept in a stock area to decrease the moisture rate. One ton of hot gas at 580 K supplied from the rotary burner or pyro-processing tower increases the raw meal production by about 1 ton per hour. The SEC reduces to 49.84 MJ/ton raw meal by transferring 40 tons/h hot gas at 580 K to the grinding system.
- Energy consumption rate for the production of cement is calculated to be 3,964.46 MJ/ton cement, which reduced to 3,779.77 MJ/ton cement by decreasing the raw meal moisture content and by the effect of waste hot gas supplied to the grinding system. After the applications, 184.69 MJ of energy is saved per ton of cement. The amount of CO_2 emissions released per MJ energy use is 0.2778 kg. Total cement production of the factory was 1,468,601 ton/year. That's, 75,343.37 tons of CO_2 emission is blocked yearly by saving 271,235.9 GJ energy.
- Similar research should be performed on the pyro-processing unit, rotary burner and grate clinker cooler systems to calculate the effects of different system parameters on the energetic, exergetic and exergoeconomic efficiencies.
- Keeping the moisture content of the raw materials used in the cement industry as low as possible can be achieved with basic measures. Significant benefits can be achieved by keeping raw materials in closed stock halls, providing products with low moisture content, and removing moisture from the raw materials with waste hot gas from the rotary kiln units.
- The cement industry is highly energy-intensive and the smallest improvements in the process will provide great benefits.

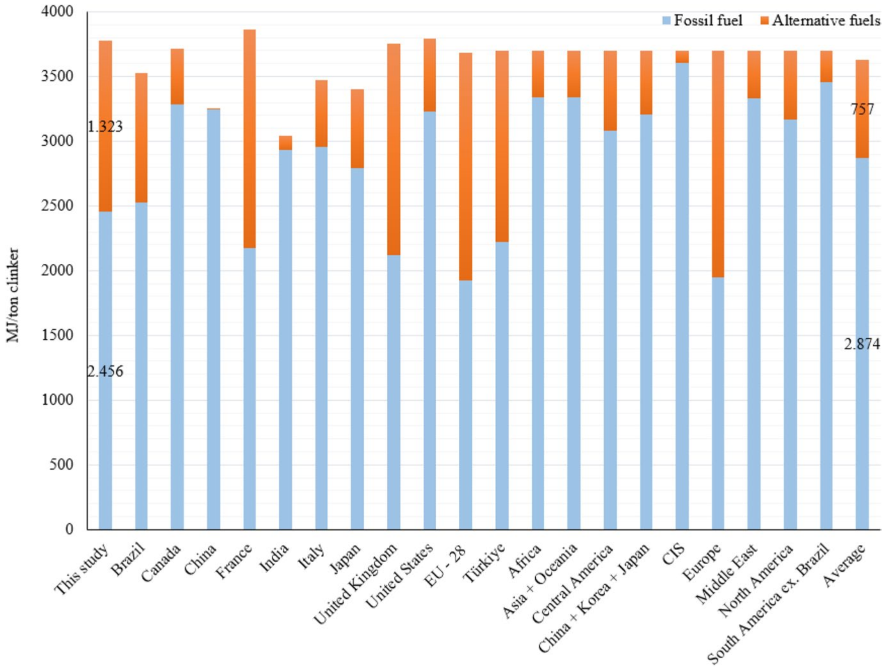


Fig. 11 Specific energy consumption per ton of clinker in selected countries and regions (IEA, 2022)

– It is concluded that this comprehensive assessment reported in this study will offer the researchers with valuable information about how sustainable the sector uses monetary, material and energy resources.

Acknowledgements The author acknowledges the support provided by the Scientific Research Projects Unit (GUBAP) at the University of Gaziantep.

Data Availability The data was acquired from private cement manufacturers in Türkiye, and they have not given their permission for researchers to share their data.

Declarations

Declaration of interests The authors declare that he has no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.The authors declare the following financial interests/personal relationships which may be considered as potential competing interests.

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