Technical Analysis Based on Exergoeconomic, Advanced Exergetic Evaluation of An In-Service Cement Production Plant With Instantaneous Process Data

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DOI: https://doi.org/10.37745/ejmer.2014/vol10n1125 Published February 15, 2023

Citation: Ikpe I.L., Abam F.I., and Odeh E.I. (2023) Technical Analysis Based on Exergoeconomic, Advanced Exergetic Evaluation of an In-Service Cement Production Plant with Instantaneous Process Data, *European Journal of Mechanical Engineering Research*, 10 (1),1-25, 2023

ABSTRACT: *An all-inclusive advanced exergy and exergoeconomic, analysis of a dry process, 5 million MTPA cement plant with real-time operational data located in Mfamosing, Cross River State, Nigeria was performed. The analysis was based on component-wise modelling by separating the exergy destruction (ED) rates into endogenous, exogenous, avoidable and unavoidable portions for the two production lines, which makes the study novel as available studies in a cement plant was based on conventional applications. The result shows an exergy efficiency (EE) of 55.58 % for L1 and 58.22 % for L2. The exergoeconomic analysis revealed that the cost of exergy destruction (COED) was higher in L2 at $14,786.40/hr with L1 calculated at $12,977.34/hr. The preheaters (PH) and Clinker Coolers (CC) contributed about 72.39 % and 59.67% for L1 and 11.09 % and 18.20 % for L2, respectively, to the overall COED. The advanced exergy analysis showed that the mainstream of the ED rates in the plant is endogenous and unavoidable. Components with high potential for improvement were identified and possible system design and optimization suggestions.*
KEYWORDS: cement, exergy, exergoeconomic, efficiency, endogenous

INTRODUCTION

The global annual cement production increased from 3.31 billion metric tons in 2010 to about 4.1 billion metric tons in 2020 [1, 2]. The cement industry is energy and material intensive, constituting about 15 % of the energy consumed in the manufacturing sector. It also accounts for about 83 % of the overall energy consumed in the making of non-metallic minerals [3, 4]. The efficiency of a cement production plant is low about 50 %, which indicates potential for improvement and reduction in environmental emissions. Additionally, a cement producing plant has an output capacity above 2500-ton clinker production per day with energy input of 4000 kJ/kg required to produce clinker [4, 5, 6]. Similarly, the clinker burning and clinker grinding consumed approximately 30 % of the electrical energy. In comparison, the raw mill accounts for about 24 % of the electricity consumption [7].

LITERATURE/ THEORETICAL REVIEWS

The application of conventional exergy analysis (CEA) exist in limited studies. Ref [8] presented a thermodynamic itemization for a cement preprocessing part. Energy and exergy efficiencies were established while [9] analyzed a cement raw mill unit. The study attained an energy efficiency of 85 %, with 25 % as exergy efficiency. Similar studies on CEA are contained in [10-12]. Studies by [13] applied the exergy principles to assess the performance of a cement rotary burner with pre-calcination in Turkey while [14] applied same principles to a cement plant in Greece. The study involves the valuation of exergy and the energy input at every production phases. The results indicate that nearly 50 % of produced exergy is lost despite the waste heat recovery system. Refs [15] and [16] investigated the raw grinding and cement mills based on exergy. The study observed areas of improvement and ascertained that the exergy analysis is a veritable tool for studying plant performance. Also, [17] analyzed a secondary kiln-shell system of a cement plant. About 42.9MWh/year and 5.30 MW of energy-saving and power respectively, was achieved, whereas [18] had concentrated on: energy utilization at the different units of the cement industries, different energy drives used in the cement industries and specific energy consumption. Recent studies on exergoeconomic analysis include the two investigations in [4] and [12]. In [4], a breakdown of step by step models required for exergoeconomic analysis was provided, and in [12], the exergoeconomic analysis was performed based on an actual cement plant in Turkey applying the developed models in [4]. The energy and exergy efficiencies were calculated at 59.37% and 38.99%, respectively. The unit exergetic value for the clinker and farine was estimated at 133.72 USD/GJ and 43.77 USD/GJ. Additionally, cement production plant analysis was only based on CEA from the reviewed studies.

Researches on advanced exergy and exergoeconomic assessment in the cement plant is uncommon in literature. Nevertheless, for better understanding of the complexity of the exergy flows in the cement production processes, it will be important to know the actual exergy destruction (ED) based on endogenous, exogenous, avoidable and unavoidable ED. To narrow this gap, the current study is aimed at performing exergoeconomic and advanced exergy analysis of an in-service cement production plant in Nigeria using actual operational data. The specifics include quantifying the inefficiencies through advanced exergy splitting (endogenous, exogenous, avoidable and unavoidable), evaluating the system's life cycle analysis, and deriving improvement prospects and transferable data important for system design and optimization.

METHODOLOGY

The approach analysis the input-output flow of exergy across thermodynamic boundaries of the system. Component wise modelling with the splitting of the exergy destruction was considered for the cement plant under study.

Universal thermodynamic modelling

The following assumptions were made: To perform the thermodynamic modelling for the cement plant, the following assumptions were made:

i. A steady-state and steady flow process.
ii. The environment pressure and temperature are the ambient conditions and constant.
iii. The potential and kinetic energy inputs and outputs are constant.
iv. Complete combustion occurs in the rotary kiln and calciner systems.
v. The gases in the flow system are ideal.
vi. Shaft work for the system is delivered by electrical energy.

Conventional energy analysis

The steady-state energy flow balance for the k^{th} component can be written as [19, 20].

$$\sum \dot{Q}_k + \sum \dot{m}_i \left(h_1 + \frac{C_i^2}{2} + gz_1\right) = \sum \dot{m}_e \left(h_0 + \frac{C_0^2}{2} + gz_0\right) + \sum \dot{W} \tag{1}$$

Where: $\dot{Q}_k$, , $\dot{m}_i$ h_1, $\frac{C_i^2}{2}$ and gz_1 are heat input, mass flow rate, enthalpy, kinetic and potential energies, respectively. In the absence of any material loss to the environment, the steady-state mass flow balance can be written as:

$$\sum \dot{m}_i = \sum \dot{m}_0 \tag{2}$$

The energy and mass balances are defined at steady-state conditions, and neglecting potential and kinetic energies:

$$\dot{Q} - \dot{W} = \sum \dot{m}_0 h_0 - \sum \dot{m}_i h_i \tag{3}$$

Conventional exergy analysis

The inefficiencies within components in thermodynamic systems can be identified using exergy techniques [21-22]. In contrast to energy analysis, exergy-based procedures account for energy quality in a system. Szargut's chemical standard exergies are applied [23]. The ambient or environmental conditions P_0 and T_0 are kept at 1.01325 bar and 25^{O}C, respectively. The exergy destruction rate $\dot{E}_{D,k}$ for k^{th} component is evaluated in Eq. (4) [24].

$$\dot{E}_{D,k} = \dot{E}_{F,k} - \dot{E}_{P,k} \tag{4}$$

The SPECO method is utilized to describe the fuel exergy rate $\dot{E}_{F,k}$ and product $\dot{E}_{P,k}$. The irreversibilities are quantified by $\dot{E}_{D,k}$ existing within a component. And so, the exergy efficiency ε_k for the specific k^{th} component is presented.

$$\varepsilon_k = \frac{\dot{E}_{P,k}}{\dot{E}_{F,k}} = 1 - \frac{\dot{E}_{D,k}}{\dot{E}_{F,k}} \qquad (5)$$

The only criterion for determining the actual thermodynamic performance of a complex system component is the ε_k [24, 25]. The ratio of exergy destruction $y^*{}_{D,k}$ is the major indicator used to ascertain the input of individual components to the overall reduction in the exergetic efficiency of the system.

$$y^*{}_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{D,tot}} \qquad (6)$$

Many times, $y^*{}_{D,k} = \frac{\dot{E}_{D,k}}{\dot{E}_{F,tot}}$ is used for analysis. For clarity, the component-wise effects of the ED will be divided by the sum of ED within all the system components [25].

Conventional exergoeconomic analysis

The exergoeconomic analysis involves the combination of the exergy and economic principles applied to thermal system analysis to maximize overall product cost. Exergoeconomic assist in understanding cost rates' distribution through energy transformation systems. The cost rate $\dot{C}_i$ of a stream, i is the product of the exergy rate $\dot{E}$ and the specific cost c_i [26].

$$\dot{C}_i = \dot{E}_i \times \dot{c}_i \qquad (7)$$

Furthermore, suppose the cost (specific costs) of every stream entering the system is ascertained. In that case, other streams are defined with a defined cost balance for the respective component and also auxiliary equations. For the k^{th} component with input (n) and output (m) streams, the general cost balance equation can be expressed as:

$$\sum_{m=1}^{n} \dot{C}_{i,k} - \sum_{j=1}^{m} \dot{C}_{j,k} + \dot{Z}_k = 0 \qquad (8)$$

$\dot{Z}_k$, represents the specific component level cost resulting from the investment, maintenance and operating overheads. Suppose the outlet streams are more than one. Then, auxiliary equations are developed to define how the costs are split amongst the other exit streams. This is evaluated following either the F-principle or the P-principle [11, 12]. The exergy destruction cost $\dot{C}_{D,k}$ for the component is calculated as:

$$\dot{C}_{D,k} = C_{F,k} \times \dot{E}_{D,k} \qquad (9)$$

Advanced exergy analysis

Endogenous/exogenous exergy destruction

The advanced exergy evaluation assists in pin-pointing system inefficiencies through component interactions. This is achieved by splitting the exergy destruction in a component system into the endogenous and the exogenous parts.

$$\dot{E}_{D,k} = \dot{E}_{D,k}^{Endo} + \dot{E}_{D,k}^{EXo} \quad (10)$$

The $\dot{E}_{D,k}^{Endo}$ (endogenous exergy destruction) defines the irreversibilities existing in the k^th^ component if it functions at equivalent εk as in actual conditions and other remaining components functions at ideal case [27]. The $\dot{E}_{D,k}^{EXO}$ (Exogenous exergy destruction) within the component, k is divided into the sum of the exogenous exergy destructions triggered by component j on k (exogenous) and exogenous exergy destruction triggered by higher-level component interactions (mexogenous).

$$\dot{E}_{D,k}^{EXO} = \sum_{j=1}^{n} \dot{E}_{D,k}^{EXoj} + \dot{E}_{D,k}^{MXO} \quad \text{With } j \neq k \quad (11)$$

Avoidable/unavoidable exergy destruction

Splitting the rate of exergy destruction (ED) into two parts, unavoidable and avoidable, within the k^th^ component offers an accurate measure for the improvement of the component efficiency. Part of exergy destroyed in a system, environmental impact and cost can be avoided with substantial structural modifications, reduction in investment costs/environmental impacts or improvements in the efficiency of the individual components. Part of the exergy destruction that is impossible to be reduced owing to technological limits, such as availability, materials cost and manufacturing methods, is termed the unavoidable $\left(\dot{E}_{D,k}^{UN}\right)$ part of the ED while the other remaining part of the ED denotes the avoidable ED $\left(\dot{E}_{D,k}^{AV}\right)$ [28-29].

Furthermore, in real case scenario the product exergy, the unavoidable ED for the k^th^ component is obtained [17-19]

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{Real} \left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN} \quad (12)$$

Where$\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN}$, is ED per unit of the product.

The avoidable ED for the kth component is present as

$$\dot{E}_{D,k}^{AV} = \dot{E}_{D,k} - \dot{E}_{D,k}^{UN} \quad (13)$$

Connecting the avoidable/ unavoidable and endogenous/exogenous ED parts

Splitting the whole ED existing in a component into the four categories: avoidable, unavoidable, endogenous and exogenous parts, next is to evaluate the ED categories for possible combinations that offer technical information. The splitting is tracked by dividing the avoidable/unavoidable to the endogenous/exogenous parts. Accordingly, the four different irreversibility parts are expressed [27-29]:

- Avoidable endogenous ED $\left(\dot{E}_{D,k}^{AV-EN}\right)$
- Avoidable exogenous ED $\left(\dot{E}_{D,k}^{AV-EX}\right)$
- Unavoidable endogenous ED $\left(\dot{E}_{D,k}^{UN-EN}\right)$

- Unavoidable exogenous ED $\left(\dot{E}_{D,k}^{UN-EX}\right)$

The avoidable/unavoidable and endogenous/exogenous parts of ED can be calculated from the expression,

$$\dot{E}_{D,k}^{UN} = \dot{E}_{P,k}^{EN}\left(\frac{\dot{E}_D}{\dot{E}_P}\right)_k^{UN} \tag{14}$$

$$\dot{E}_{D,k}^{AV-EN} = \dot{E}_{D,k}^{EN} - \dot{E}_{D,k}^{UN-EN} \tag{15}$$

$$\dot{E}_{D,k}^{UN-EX} = \dot{E}_{D,k}^{UN} - \dot{E}_{D,k}^{UN-EN} \tag{16}$$

$$\dot{E}_{D,k}^{AV-EX} = \dot{E}_{D,k}^{EX} - \dot{E}_{D,k}^{UN-EX} \tag{17}$$

The $\dot{E}_{D,k}^{AV-EN}$ can be reduced component improvement. Also, the reduction in $\left(\dot{E}_{D,k}^{AV-EX}\right)$ is achievable by improving other components of the system [31]. The $\dot{E}_{D,k}^{UN-EN}$, and $\dot{E}_{D,k}^{UN-EX}$ exist as a consequence of the thermodynamic limitations.

Process plant description

Figure 1 presents the cement production plant's material and process simulation flow. Limestone and additives are crushed with electricity input at stage 1 to 4 (Figure 1). These are piled separately and consumed in required proportions from stage (5) to (8) and fed into the raw mill at (9), where milling occurs at (10). The power from (10) drives the mill and process hot air (11) from the rotary kiln at 350 °C, which support drying and grinding. The fine raw meal is separated and transported through induced air (12) to the raw meal silos, and collected at (13), where the hot air and process emissions are discharged at (14). The control volume of the raw meal (16) is fed from the silos through the preheater cyclones, which undergoes both drying and precalcination at (18), where the kiln flow in the reverse direction to the flow of the raw meal occasioned by the effect of the induced draft fan (17). Material leakage (19), heat exchanges and losses (21) occurs at the preheater with air discharge (22). The precalcined material (20) flows into the rotary kiln at (23). Further heating, decarbonization, and clinkerization occur at about 1450 °C to form clinker. At this temperature which is generated by the combustion of fossil and other fuels (25) in the presence of air (26) and recuperated heat from the clinker cooler (24). The clinker (34) exit the cooler at about 70 to 180°C and transported to the clinker silos for storage. Fine clinker particles exit at (32). The suction fan (14) expelled the air and attendant emissions through the chimney. Similarly, the controlled volume of the clinker (35) is extracted from the clinker silos to the cement mill (38) alongside additives such as gypsum (36) and high-grade limestone's (37). The milled cement (41) is transported to the cement silos. Air and the corresponding emissions (40), and the heat losses (39) are discharged by the effect of the suction fans (41). Cement from the silos (42) is packed and shipped (46) either in bulk tanker and or in bags of given sizes to the final consumer with power input (43) to the packing machine and outputs of air, heat losses (44) and fugitive dust (45) which is trapped by dust collectors across the packing lines. The energy balances in the component system of Figure1 are simplify as shown in the block schematic of energy flow in the specific components presented in Figure 2. The mass, energy and exergy balances for the Figure 2 are depicted in Table 1.

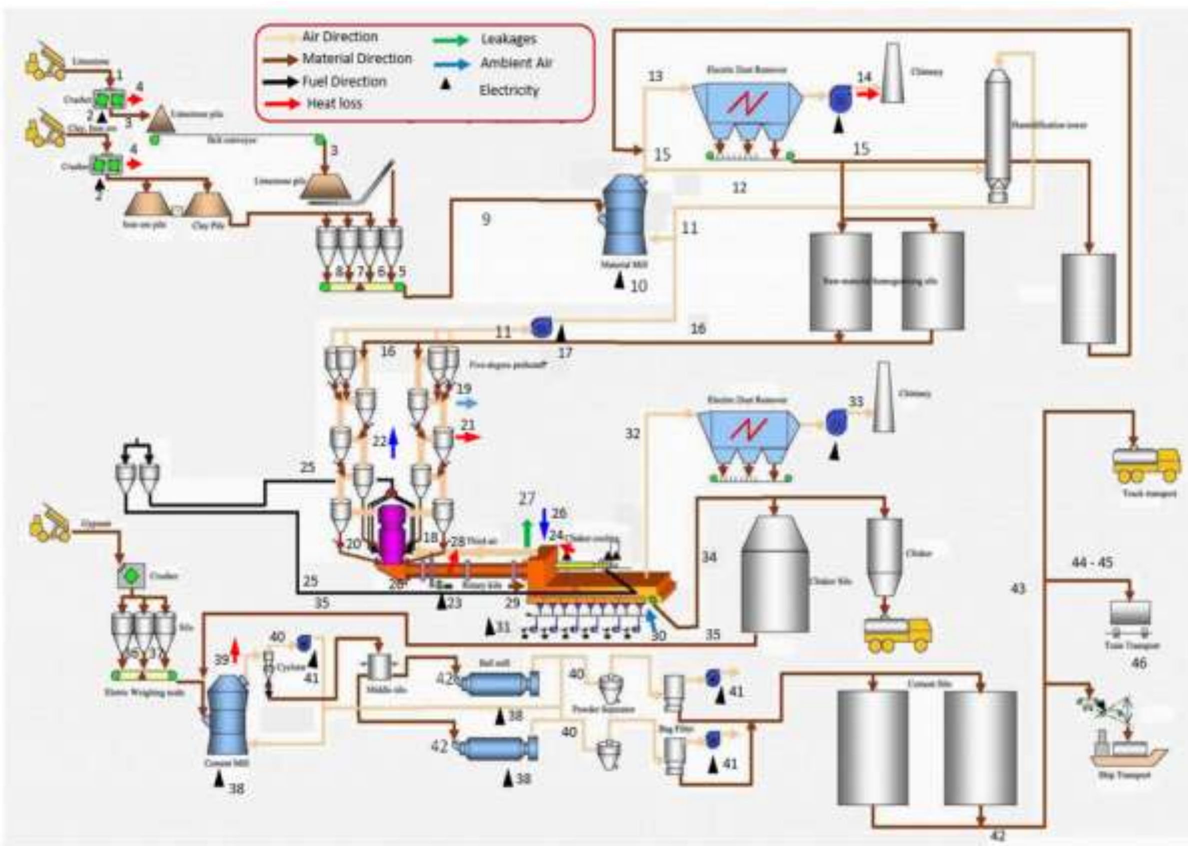


Fig 1: Flow diagram and material process simulation of the cement plant

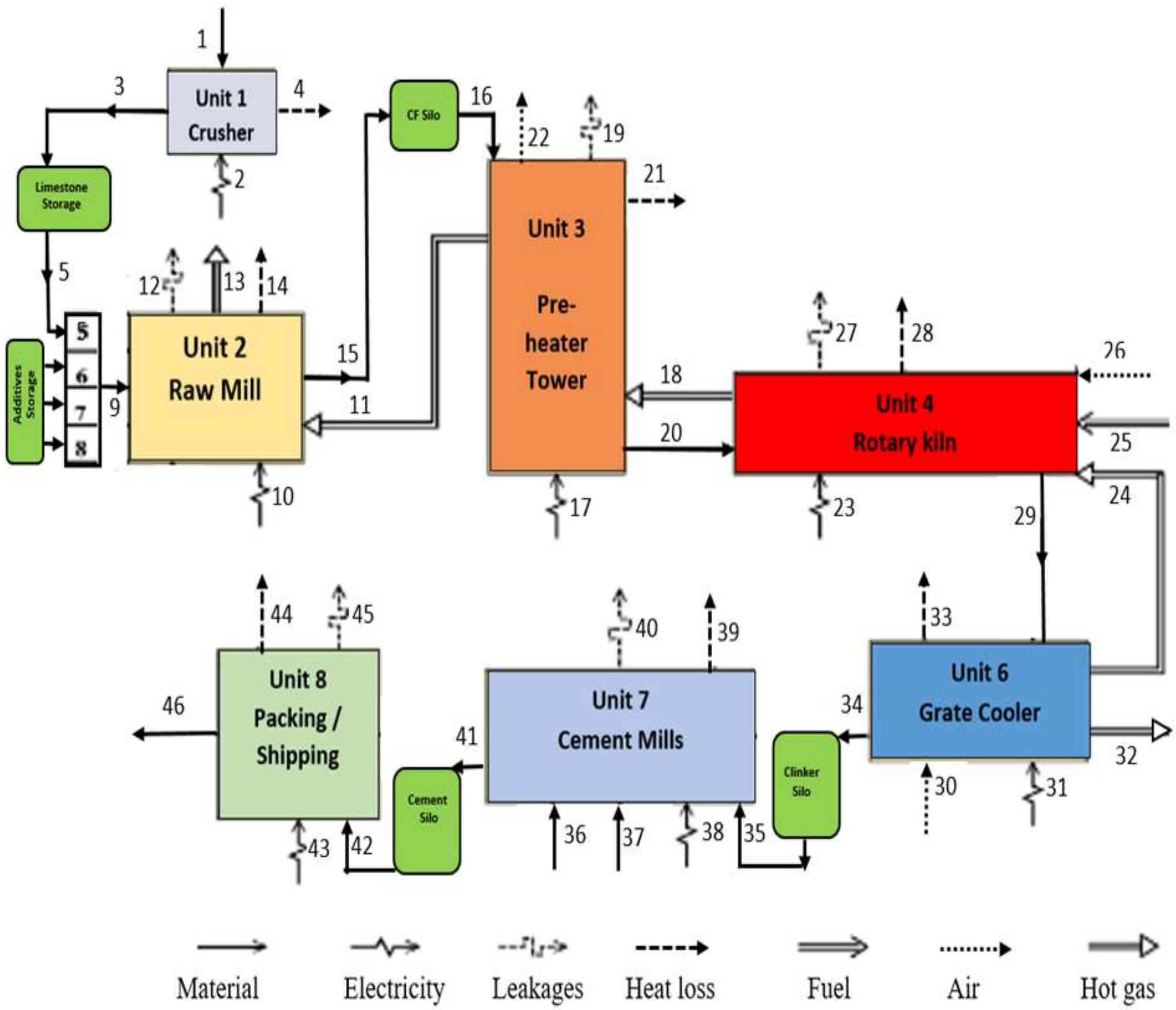
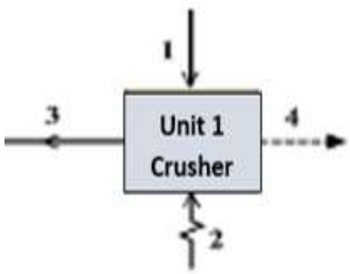


Figure 2. Simplify block schematic of inlet and exit energy flow stream in the components

Table 1
Energy and exergy balances for the principal units of the cement plant from (Figure 2).

Units Schematics

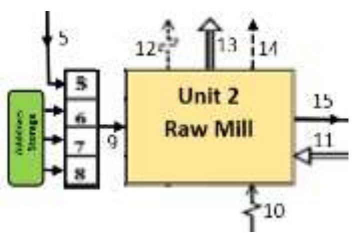
1. Crusher



Mass, energy and exergy flow balances

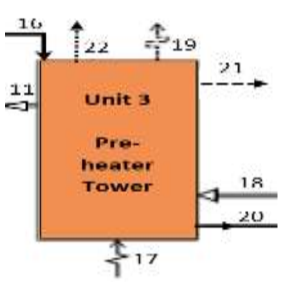
$$\dot{m}_1 = \dot{m}_3 = \dot{m}_{limestone}$$
$$\dot{m}_1 h_1 + \dot{m}_2 h_2 = \dot{m}_3 h_3 + \dot{m}_4 h_4$$
$$\dot{E}_D = (\dot{E}_2 + \dot{E}_1) - (\dot{E}_3 + \dot{E}_4)$$
$$\eta_I = \frac{\dot{m}_3 h_3}{\dot{m}_1 h_1 + \dot{m}_2 h_2}$$
$$\eta_{II} = \frac{\dot{E}_3 + \dot{E}_4}{\dot{E}_1 + \dot{E}_2}$$

2. Raw Grinding



$$\dot{m}_5 + \dot{m}_6 + \dot{m}_7 + \dot{m}_8 = \dot{m}_9$$
$$\dot{m}_9 + \dot{m}_{11} = \dot{m}_{12} + \dot{m}_{13} + \dot{m}_{15}$$
$$\dot{m}_{11} = \dot{m}_{13} = \dot{m}_{hotgas}$$
$$\dot{m}_5 h_5 + \dot{m}_6 h_6 + \dot{m}_7 h_7 + \dot{m}_8 h_8 = \dot{m}_9 h_9$$
$$\dot{m}_9 h_9 + \dot{m}_{10} h_{10} + \dot{m}_{11} h_{11} = \dot{m}_{12} h_{12} + \dot{m}_{13} h_{13} + \dot{m}_{14} h_{14} + \dot{m}_{15} h_{15}$$
$$\dot{E}_5 + \dot{E}_6 + \dot{E}_7 + \dot{E}_8 = \dot{E}_9$$
$$\dot{E}_D = (\dot{E}_9 + \dot{E}_{10} + \dot{E}_{11}) - (\dot{E}_{12} + \dot{E}_{13} + \dot{E}_{14} + \dot{E}_{15})$$
$$\eta_I = \frac{\dot{m}_{12} h_{12} + \dot{m}_{13} h_{13} + \dot{m}_{15} h1_5}{\dot{m}_9 h_9 + \dot{m}_{10} h_{10} + \dot{m}_{11} h_{11}}$$
$$\eta_{II} = \frac{\dot{E}_{12} + \dot{E}_{13} + \dot{E}_{14} + \dot{E}_{15}}{\dot{E}_9 + \dot{E}_{10} + \dot{E}_{11}}$$

3. Preheater cyclones tower



$$\dot{m}_{16} + \dot{m}_{18} = \dot{m}_{11} + \dot{m}_{19} + \dot{m}_{20} + \dot{m}_{21}$$
$$\dot{m}_{16} = \dot{m}_{19} + \dot{m}_{20} = \dot{m}_{farine}$$
$$\dot{m}_{18} = \dot{m}_{11} + \dot{m}_{21} = \dot{m}_{hotgas}$$
$$\dot{m}_{16} h_{16} + \dot{m}_{17} h_{17} + \dot{m}_{18} h_{18} = \dot{m}_{11} h_{11} + \dot{m}_{19} h_{19} + \dot{m}_{20} h_{20} + \dot{m}_{21} h_{21} + \dot{m}_{22} h_{22}$$
$$\dot{E}_D = (\dot{E}_{16} + \dot{E}_{17} + \dot{E}_{18}) - (\dot{E}_{11} + \dot{E}_{19} + \dot{E}_{20} + \dot{E}_{21} + \dot{E}_{22})$$
$$\eta_I = \frac{\dot{m}_{11} h_{11} + \dot{m}_{19} h_{19} + \dot{m}_{21} h_{21} + \dot{m}_{22} h_{22}}{\dot{m}_{16} h_{16} + \dot{m}_{17} h_{17} + \dot{m}_{18} h_{18}}$$
$$\eta_{II} = \frac{\dot{E}_{11} + \dot{E}_{19} + \dot{E}_{20} + \dot{E}_{21} + \dot{E}_{22}}{\dot{E}_{16} + \dot{E}_{17} + \dot{E}_{18}}$$

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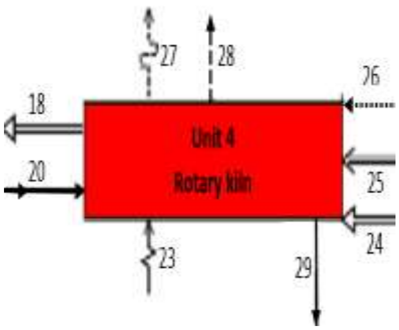
4 Rotary Kiln



$$\dot{m}_{20} + \dot{m}_{24} + \dot{m}_{25} + \dot{m}_{26} = \dot{m}_{18} + \dot{m}_{27} + \dot{m}_{29}$$

$$\dot{m}_{20} = 0.58x\dot{m}_{29} = \dot{m}_{farine-clinker}$$

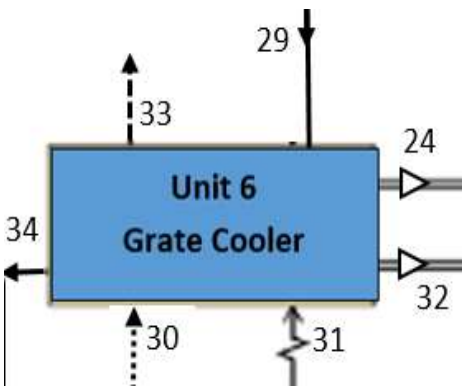
$$\dot{m}_{20}h_{20} + \dot{m}_{23}h_{23} + \dot{m}_{24}h_{24} + \dot{m}_{25}h_{25} + \dot{m}_{26}h_{26} = \dot{m}_{18}h_{18} + \dot{m}_{27}h_{27} + \dot{m}_{28}h_{28} + \dot{m}_{29}h_{29}$$

$$\dot{E}_D = (\dot{E}_{20} + \dot{E}_{23} + \dot{E}_{24} + \dot{E}_{25} + \dot{E}_{26}) - (\dot{E}_{18} + \dot{E}_{27} + \dot{E}_{28} + \dot{E}_{29})$$

$$\eta_I = \frac{\dot{m}_{18}h_{18}+\dot{m}_{27}h_{27}+\dot{m}_{28}h_{28}}{\dot{m}_{20}h_{20}+\dot{m}_{23}h_{23}+\dot{m}_{24}h_{24}+\dot{m}_{25}h_{25}+\dot{m}_{26}h_{26}}$$

$$\eta_{II} = \frac{\dot{E}_{18}+\dot{E}_{27}+\dot{E}_{28}+\dot{E}_{29}}{\dot{E}_{20}+\dot{E}_{23}+\dot{E}_{24}+\dot{E}_{25}+\dot{E}_{26}}$$

5 Grate cooler



$$\dot{m}_{29} + \dot{m}_{30} = \dot{m}_{24} + \dot{m}_{32} + \dot{m}_{33} = \dot{m}_{hot-cold,clinker}$$

$$\dot{m}_{29}h_{29} + \dot{m}_{30}h_{30} + \dot{m}_{31}h_{31} = \dot{m}_{24}h_{24} + \dot{m}_{32}h_{32} + \dot{m}_{33}h_{33} + \dot{m}_{34}h_{34}$$

$$\dot{E}_D = (\dot{E}_{29} + \dot{E}_{30}+\dot{E}_{31}) - (\dot{E}_{24} + \dot{E}_{32} + \dot{E}_{33} + \dot{E}_{34})$$

$$\eta_I = \frac{\dot{m}_{24}h_{24}+\dot{m}_{32}h_{32}+\dot{m}_{33}h_{33}+\dot{m}_{34}h_{34}}{\dot{m}_{29}h_{29}+\dot{m}_{30}h_{30}+\dot{m}_{31}h_{31}}$$

$$\eta_{II} = \frac{\dot{E}_{24} + \dot{E}_{32} + \dot{E}_{33} + \dot{E}_{34}}{\dot{E}_{29} + \dot{E}_{30} + \dot{E}_{31}}$$

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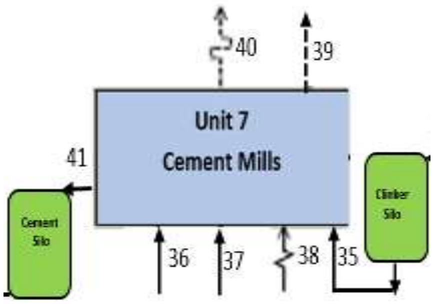
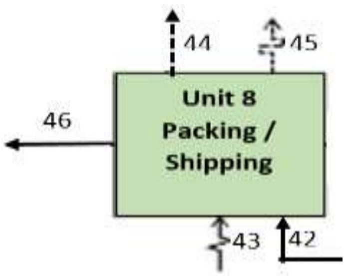
6 Cement mill



$$\dot{m}_{35} + \dot{m}_{36} + \dot{m}_{37} = \dot{m}_{39} + \dot{m}_{40} + \dot{m}_{41}$$
$$\dot{m}_{35}h_{35} + \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37} + \dot{m}_{38}h_{38} = \dot{m}_{39}h_{39} + \dot{m}_{40}h_{40} + \dot{m}_{41}h_{41}$$
$$\dot{E}_D = (\dot{E}_{35} + \dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38}) - (\dot{E}_{39} + \dot{E}_{40} + \dot{E}_{41})$$
$$\eta_I = \frac{\dot{m}_{40}h_{40} + \dot{m}_{41}h_{41}}{\dot{m}_{35}h_{35} + \dot{m}_{36}h_{36} + \dot{m}_{37}h_{37} + \dot{m}_{38}h_{38}}$$
$$\eta_{II} = \frac{\dot{E}_{39} + \dot{E}_{40} + \dot{E}_{41}}{\dot{E}_{35} + \dot{E}_{36} + \dot{E}_{37} + \dot{E}_{38}}$$

7 Packing plant



$$\dot{m}_{42} = \dot{m}_{46} = \dot{m}_{cement}$$
$$\dot{m}_{42} = \dot{m}_{46} = \dot{m}_{cement}$$
$$\dot{m}_{42}h_{42} + \dot{m}_{43}h_{43} = \dot{m}_{44}h_{44} + \dot{m}_{45}h_{45} + \dot{m}_{46}h_{46}$$
$$\dot{E}_D = (\dot{E}_{42} + \dot{E}_{43}) - (\dot{E}_{44} + \dot{E}_{45} + \dot{E}_{46})$$
$$\eta_I = \frac{\dot{m}_{45}h_{45} + \dot{m}_{46}h_{46}}{\dot{m}_{42}h_{42} + \dot{m}_{43}h_{43}}$$
$$\eta_{II} = \frac{\dot{E}_{44} + \dot{E}_{45} + \dot{E}_{46}}{\dot{E}_{42} + \dot{E}_{43}}$$

Operating data collection and analysis

The daily operation data for the productions lines L1 and L2 were obtained from the cement control process log sheet. The kiln process reports contain the mass flow rate, kiln inlet and outlet conditions, and preheater exit conditions. Similarly, the state point's condition of Figure 1 is shown in Table 2, which were actual data obtained from the system process units. Codes were written in an excel spreadsheet and Engineering Equation Solver (EES) to compute system data. The exergy flow rates (E) for the state points were calculated following the assumptions in this study depicted in Table 2.

Table 2
Real-time operating data and exergy flow rates for the cement production plants for L1 & L2

Stream	LINE 1					LINE 2				
	m t/h	m (kg/s)	T (^{O}C)	P (mbar)	E (kW)	m (t/h)	m (kg/s)	T (^{O}C)	P (mbar)	E (kW)
1	1501.0	416.9	20.0	1.0	7588.4	1501.0	416.94	20.0	1.0	7,588.39
2	0.0	1.0	0.00	0.0	3450.0	0.0	0.00	0.0	0.0	3,450.00
3	1501.0	416.9	20.0	1.0	7,588.39	1501.0	416.94	20.0	1.0	7,588.39
4	0.0	0.0	20.0	1.0	623.10	0.0	0.00	20.0	1.0	623.10
5	16.0	4.4	25.0	-8.1	101.11	20.0	5.56	25.0	-7.8	126.39
6	13.0	3.6	25.0	-8.1	82.15	0.0	0.00	25.0	-7.8	-
7	52.0	14.4	25.0	-8.1	328.61	31.0	8.61	25.0	-7.8	195.90
8	426.0	118.3	25.0	-8.1	2,692.08	474	131.67	25.0	-7.8	2,995.42
9	507.0	140.8	25.0	-8.1	3,203.96	525.0	145.83	25.0	-7.8	7,856.33
10	0.0	0.0	0.0	-8.1	7,730.00	0.0	0.00	233.3	-7.8	9,050.00
11	26.1	7.3	350.0	42.0	3,823.91	32.0	8.89	364.0	39	1,494.00
12	3.0	0.8	138.0	-3.5	86.89	6.8	1.89	136.0	-3.5	190.80
13	26.1	7.3	138.0	-3.5	1,398.67	32	8.89	138.0	-3.5	1,828.09
14	1.2	0.3	138.0	-3.5	64.31	0.8	0.22	136.0	-3.5	46.11
15	504.0	140.0	87.5	-71.2	7,961.84	518.2	143.94	84.2	72.3	7,754.58
16	347.8	96.6	323.0	2.0	16,875.01	401.6	111.56	320.0	2.0	21,318.53
17	0.0	1.0	0.0	0.0	4,200.00	1.0	0.28	0.0	39.0	3,320.00
18	40.4	11.2	1014.0	36.0	11,229.20	60.7	16.86	889.0	37.9	3,705.48
19	0.8	0.2	350.0	42.0	222.36	48.3	13.42	364.0	39.0	1,359.44
20	347.0	96.4	1014.0	-1.3	18,924.99	420.0	116.67	1076.0	-0.7	16,031.87
21	14.3	4.0	350.0	42.0	2,095.09	28.7	7.97	364.0	39.0	1,095.51
22	3.0	0.8	350.0	42.0	439.53	12.0	3.33	364.0	39.0	234.17
23	239.0	1.0	25.0	-0.3	1,980.00	3170.0	880.56	0.0	0.0	3,170.00
24	40.4	11.2	814.0	-0.4	3,382.29	407.1	113.08	850.0	-0.4	6,646.07
25	8.4	2.3	60.0	-0.4	9,886.43	8.1	2.25	63.0	-0.4	7,349.87
26	8.4	2.3	60.0	-0.4	140.70	8.1	2.25	63.0	-0.4	142.22
27	52.1	14.5	298.8	-0.4	1,437.64	63.0	17.50	287.5	-0.4	1,899.84
28	32.9	9.2	279.4	-0.4	944.30	39.9	11.08	288.2	-0.4	1,201.10
29	295.0	81.9	814.0	-0.4	3,162.52	357.0	99.17	850.0	-0.4	4,325.45
30	88.7	24.6	25.0	64.4	19,537.28	82.2	22.83	25.0	-0.4	18,931.69
31	0.0	0.0	25.0	36.0	2,228.00	82.2	22.83	25.0	-0.4	3,469.00
32	45.7	12.7	173.4	36.0	2,499.64	13.3	3.69	151.3	37.9	619.07
33	2.6	0.7	173.4	36.0	142.21	1.8	0.50	151.3	37.9	83.78
34	292.4	81.2	173.4	-0.4	10,040.41	355.2	98.67	151.3	-4.0	13,305.49
35	144.0	40.0	39.3	0.7	460.88	307.6	85.45	40.1	-4.0	930.44
36	24.6	6.8	39.3	0.7	78.73	55.0	15.28	87.7	-4.0	25.92
37	5.1	1.4	39.3	0.7	76.36	6.0	1.67	87.7	-4.0	13.33
38	0.0	0.0	0.00	0.7	15,636.00	0.0	0.00	0.00	0.7	15,110.00
39	1.7	0.5	92.0	0.7	20.90	0.9	0.25	90.8	0.7	10.65
40	2.1	0.6	92.0	5.1	25.82	36.0	10.00	91.5	39.3	432.05
41	169.9	47.2	99.0	5.1	2,366.15	331.7	92.14	96.5	-4.0	4,366.72
42	120.0	33.3	76.0	0.7	280.00	120.0	33.33	76.0	8.2	280.00
43	950.0	263.9	76.0	0.7	950.00	950.0	0.00	76.0	0.7	950.00
44	1.0	0.3	66.0	0.7	2.33	1.0	0.28	66.0	0.7	2.33
45	1.0	0.3	66.0	0.7	2.33	1.0	0.28	66.0	0.7	2.33
46	120.0	33.3	66.0	0.7	280.00	120.0	33.33	66.0	0.7	280.00

RESULTS

Conventional exergy-based analyses

Figure 3 presents the overall exergy efficiencies and the exergetic variances of the L1 and L2. The efficiencies were calculated at 58.22 % and 55.58 % respectively. The exergy of fuel (EF), exergy of production (EP) and exergy destruction (ED) ranged between $135.16 \leq \text{EF} \leq 135.29$ MW, $75.13 \leq \text{EF} \leq 78.77$MW and $56.52 \leq \text{ED} \leq 60.03$ MW in that order. However, a variance of 3.51MW in the total rate of ED for L1 and L1 was observed, with L2 having the highest ED, of 3.64 MW loss in EP.

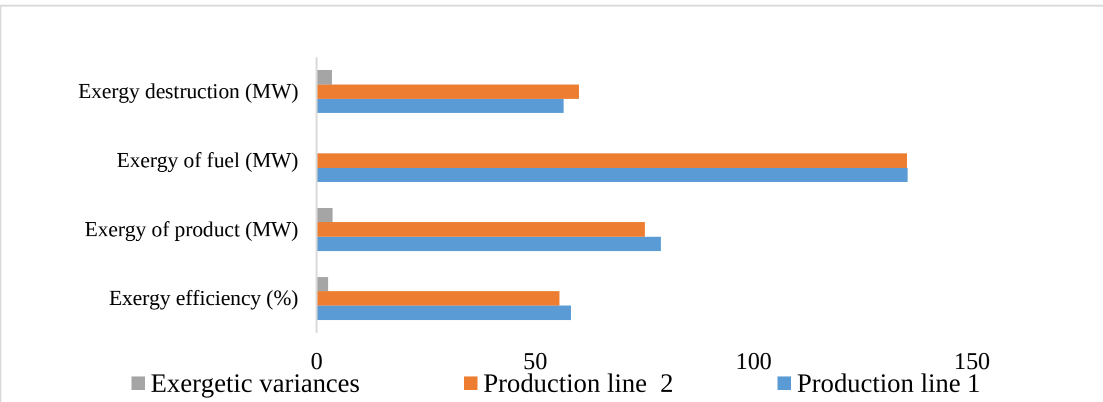


Figure 3. Overall exergy details in the cement production line.

Conventional exergoeconomic-based analyses

Table 3 presents the exergoeconomic results for the two L1 and L2, comprising: the equipment cost rate, ($\dot{Z}$ k) cost of ED, ($\dot{C}_{D,k}$), the EP and EF cost and exergoeconomic factor (f_k). The largest $\dot{c}_{D,k}$ occurred at the preheater calculated at 9,394.87 $/h (L1) and 8,824.26 $/h (L2). However, this is evident in the design of the preheater cyclones towers in which L1 with single 5-stage preheater cyclone system, whereas L2 has a double inline 5-stage cyclone for better material hot gas heat exchanges. The clinker cooler is the next largest in ED cost 1,439.69 $/h (L1) and 2,691.82 $/h (L2). The ($f_k$) are lowest for RM and CM components in the two lines. The kiln and the CM had the highest f_k. Low values of (f_k) denotes high $\dot{c}_{D,k}$ and indicates high improvement potential.

Table 3
Exergoeconomic parameters for main components of the cement plant (Line 1 and 2)

Component	Ɛk (%)	$\dot{c}_{F,k}$ ($/GJ)	$\dot{c}_{P,k}$ ($/GJ)	$\dot{C}_{D,k}$($/h)	$\dot{Z}$ k ($/h)	$Z + \dot{C}_D$ ($/h)	f_k(%)	r_k(%)
LINE 1								

European Journal of Mechanical Engineering Research, 10 (1),1-25, 2023
Print ISSN: ISSN 2055-6551(Print)
Online ISSN: ISSN 2055-656X(Online
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CR	74.39	37.25	27.71	704.21	694.78	1,398.98	49.66	1.3
RM	64.45	97.20	50.80	1,072.40	44.24	1,116.65	3.96	0.2
PH	78.96	109.00	165.76	9,394.87	4,189.70	13,584.57	30.84	1.8
Kiln	48.88	103.90	30.12	296.40	5,428.16	5,724.55	94.82	0.3
CL	64.44	18.19	54.21	1,439.69	154.81	1,594.50	9.71	1.0
CM	14.44	54.84	8.32	68.09	2,904.49	2,972.58	97.71	0.4
PP	23.14	11.92	1.90	1.68	10.01	11.69	85.62	0.1
LINE 2								
CR	74.39	37.25	27.71	704.21	694.78	1,398.98	49.66	1.3
RM	53.37	113.67	57.87	1,507.37	264.41	1,242.95	21.27	0.1
PH	71.32	95.64	142.23	8,824.26	3,002.82	11,827.08	25.39	1.5
Kiln	33.39	89.59	47.48	825.20	3,611.77	4,436.97	81.40	0.2
CL	77.28	26.30	69.69	2,691.82	395.11	3,086.94	12.80	1.9
CM	29.91	54.26	14.86	231.64	2,552.29	2,783.93	91.68	0.5
PP	23.14	4.15	1.90	1.90	10.01	11.92	84.01	0.3

Advanced exergy analysis for the cement plant

The results of the advanced exergy analysis are presented in Tables 4 and 5. The $\dot{E}_D^{EN} > \dot{E}_D^{EX}$ in the components except for CR and CC (L1) (Table 6) while $\dot{E}_D^{EX} > \dot{E}_D^{EN}$ in CR, RM, PH and PP components (L2) (Table 7).

Tables 4 and 5 also show that the overall $\dot{E}_{Dover.}^{UN}$ (unavoidable exergy destruction) in the components is far higher than the avoidable exergy destruction $\dot{E}_{Dover.}^{AV}$. The values of $\dot{E}_{Dover.}^{UN}$ and $\dot{E}_{Dover.}^{AV}$ stood at 51,826.04 and 4,694.67 kW (L1) and 51,732.44 and 8,299.72 kW (L2). The RK and CMB components are highly responsible for the high $\dot{E}_{Dover.}^{UN}$ whose values were ranged between $16{,}037.37 \leq \dot{E}_D^{UN} \leq 18{,}417.95\ kW$ and $10{,}232.87 \leq \dot{E}_D^{UN} \leq 14{,}023.05\ kW$ for L1 and L2, respectively. However, the overall improvement potential (IMP) (Figure 4) was 23,613.69 kW for L1 and 26,663.94 kW for L2. The result shows a high IMP for L2 while components like RK and CMB, which constituted the highest $\dot{E}_D^{UN}$ show an impressive IMP of about 8,966 Kw and 14,793 kW(L1), and 12,235kW and 7,899 Kw(L2), respectively

Table 4
Results of the advanced exergy analysis at the component level for Line 1 (KW)

Component	$\dot{E}_{D,k}^{real}$	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$
CR	2,826.90	623.10	2,203.80	2,612.39	214.51	575.82	2036.57	47.28	167.23
RM	5,246.16	1,398.67	3,847.49	5,162.77	83.39	1,376.44	3786.34	22.23	61.16
PH	6,798.32	4,200.00	2,598.32	6,063.47	734.84	3,746.01	2317.46	453.99	280.86
RK	17,540.76	11,866.43	5,674.33	16,037.37	1,503.39	10,849.38	5187.99	1,017.05	486.34
CC	8,863.25	2,228.00	6,635.25	6,997.15	1,866.10	1,758.91	5238.24	469.09	1,397.01
CBM	14,299.98	11,727.00	2,572.98	14,023.05	276.93	11,499.90	2523.16	227.10	49.83
PP	945.33	712.50	232.83	929.84	15.50	700.82	229.02	11.68	3.82
Overall	56,520.71	32,755.70	23,765.01	51,826.04	4,694.67	30,507.27	21,318.77	2,248.43	2,446.24

Print ISSN: ISSN 2055-6551(Print)
Online ISSN: ISSN 2055-656X(Online
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Table 5
Results of the advanced exergy analysis at the component level for Line 2 (KW)

Component	$\dot{E}_{D,k}^{real}$	$\dot{E}_{D,k}^{EN}$	$\dot{E}_{D,k}^{EX}$	$\dot{E}_{D,k}^{UN}$	$\dot{E}_{D,k}^{AV}$	$\dot{E}_{D,k}^{UN,EN}$	$\dot{E}_{D,k}^{UN,EX}$	$\dot{E}_{D,k}^{AV,EN}$	$\dot{E}_{D,k}^{AV,EX}$
CR	2,826.90	623.10	2,203.80	2,612.39	214.51	575.82	2,036.57	47.28	167.23
RM	8,580.77	1,828.09	6,752.68	8,373.75	207.02	1,783.99	6,589.76	44.10	162.91
PH	8,129.02	3,320.00	4,809.02	7,047.65	1,081.37	2,878.35	4,169.29	441.65	639.73
RK	22,208.15	10,519.87	11,688.28	18,417.95	3,790.20	8,724.48	9,693.48	1,795.39	1,994.80
CC	6,071.72	3,469.00	2,602.72	4,117.99	1,953.73	2,352.76	1,765.23	1,116.24	837.49
CBM	11,270.27	10,577.00	693.27	10,232.87	1,037.40	9,603.41	629.46	973.59	63.81
PP	945.33	712.50	232.83	929.84	15.50	700.82	229.02	11.68	3.82
Overall	60,032.16	31,049.56	28,982.60	51,732.44	8,299.72	26,619.63	25,112.81	4,429.93	3,869.79

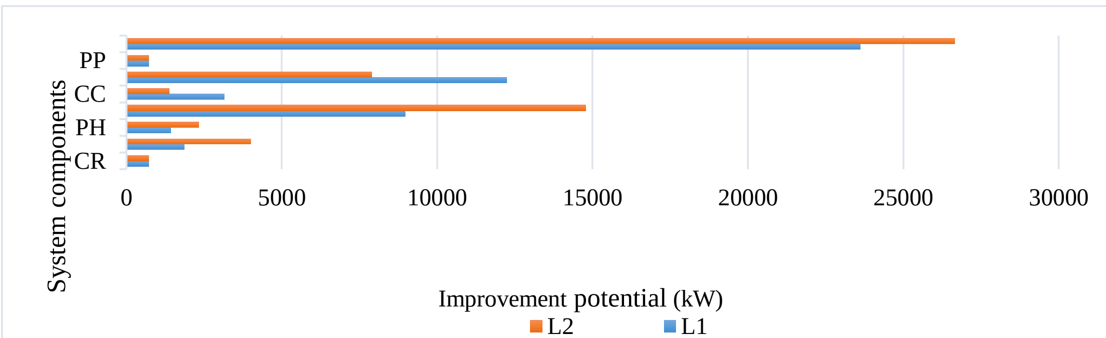

Figure 4. Improvement potential (IP) of plant components for L1 and L2

Separating the Components' Exergy Destruction rate

The splitting of the exergy destruction rate of the cement plant components into exogenous, endogenous, avoidable, unavoidable, exogenous-unavoidable, exogenous-avoidable, endogenous-unavoidable and endogenous-avoidable for L1 and L2 are indicated in Figure 5 and 6. Equally, the contribution of each component into the overall exogenous, endogenous, avoidable, unavoidable, exogenous-unavoidable, exogenous-avoidable, endogenous-unavoidable and endogenous-avoidable is presented in (Figure. 7a and 7b) for L1 and L2. From Figure 5 and 6, it is observed that a large part of exergy destruction is unavoidable $\dot{E}_D^{UN}$ with a maximum at 98 % for both L1 and L2, while the least exergy destruction is the available endogenous (AV-EN), which range between $1 \leq AV - EN \leq 59\,\%$ for L1 and $0.59 \leq AV - EN \leq 28\,\%$. Other forms of ED splitting are shown in Figs.5 and 6.

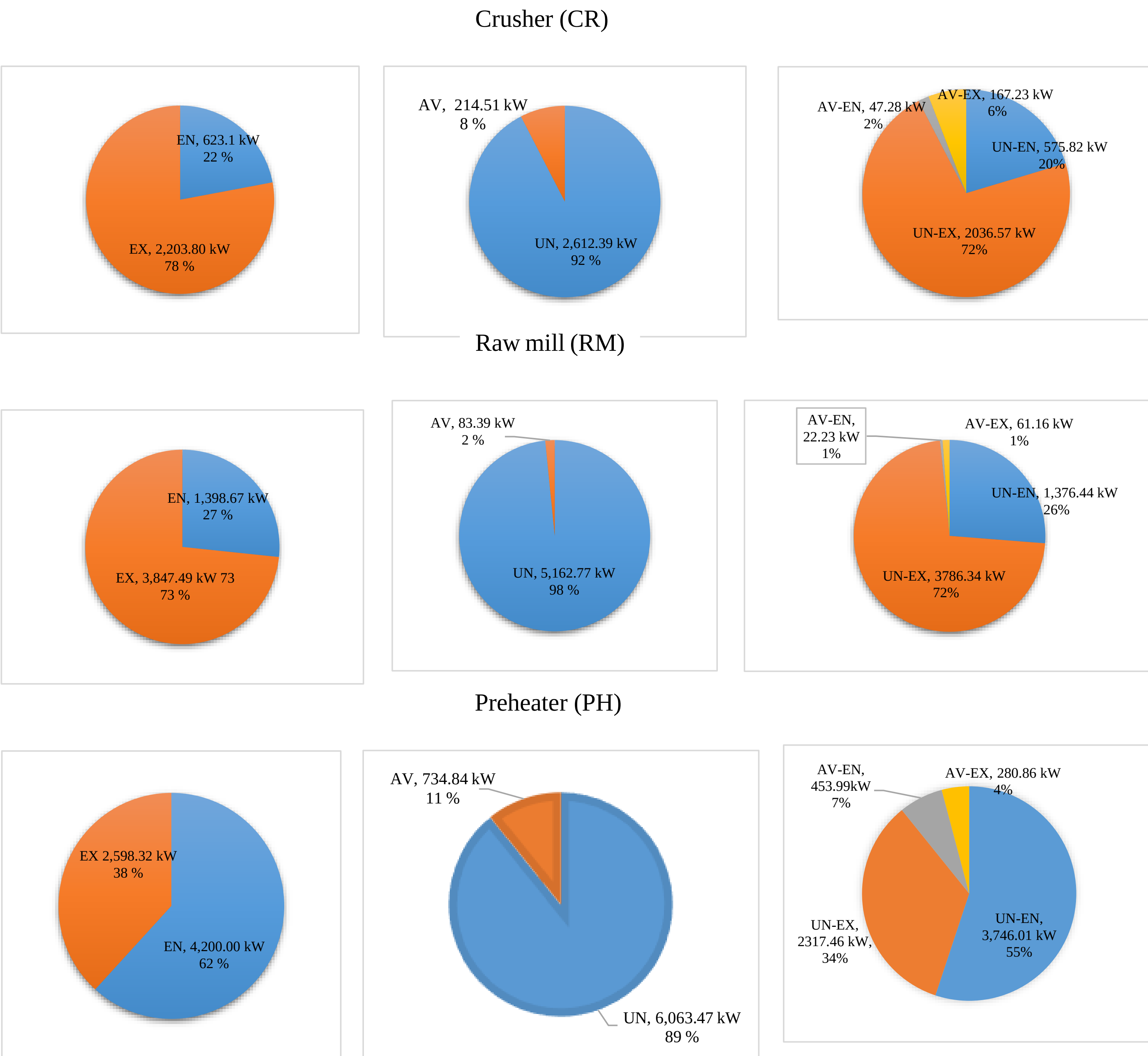

Figure 5. The splitting the components system ED rate into Exogenous, Endogenous, unavoidable, avoidable, endogenous-unavoidable, endogenous-avoidable, Exogenous-unavoidable and exogenous-avoidable parts for L1

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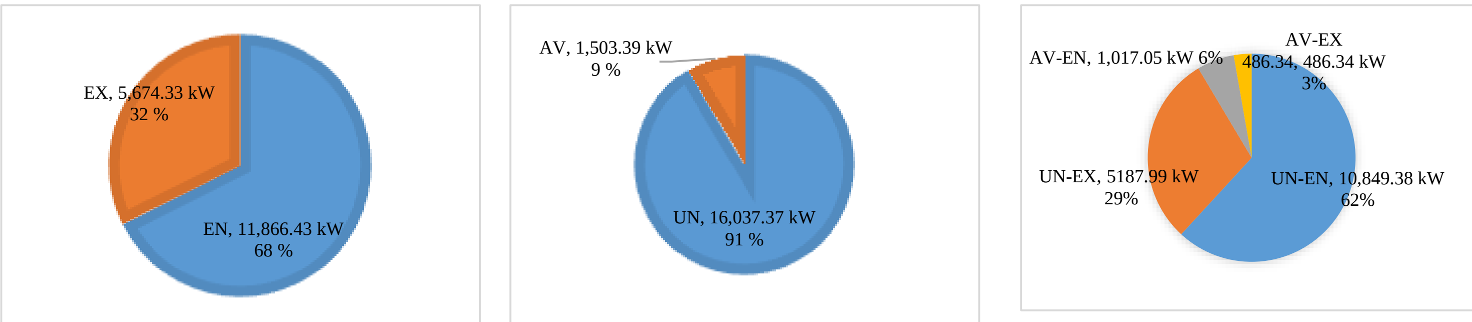
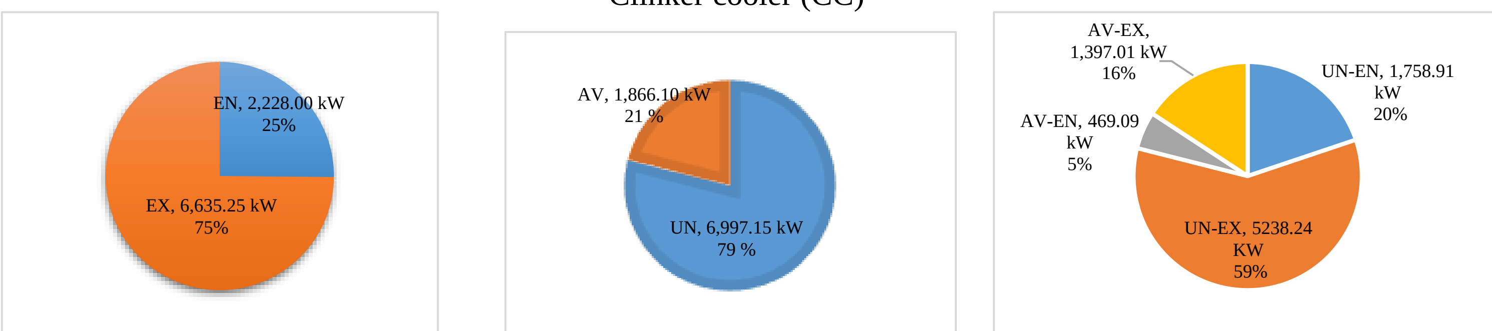
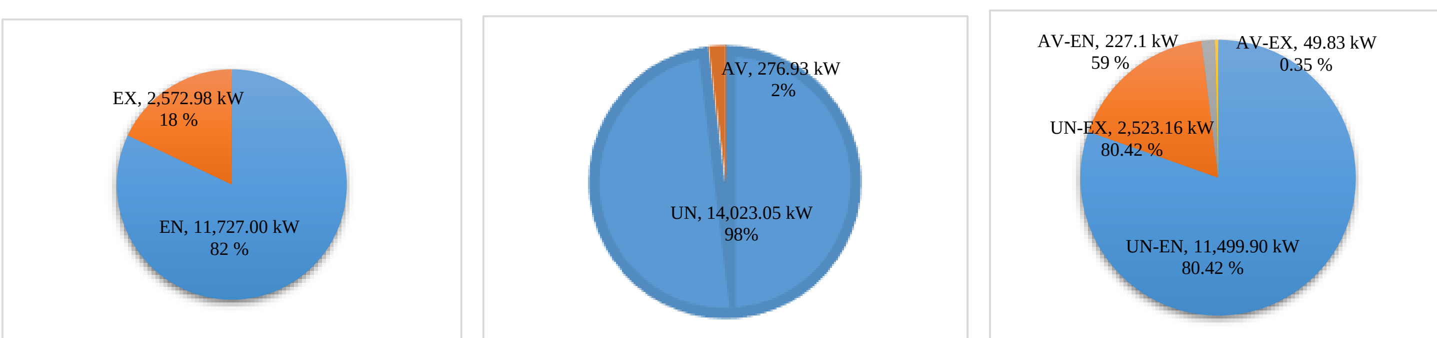
Rotary Kiln (RK)



Clinker cooler (CC)



Cement ball mill (CBM)



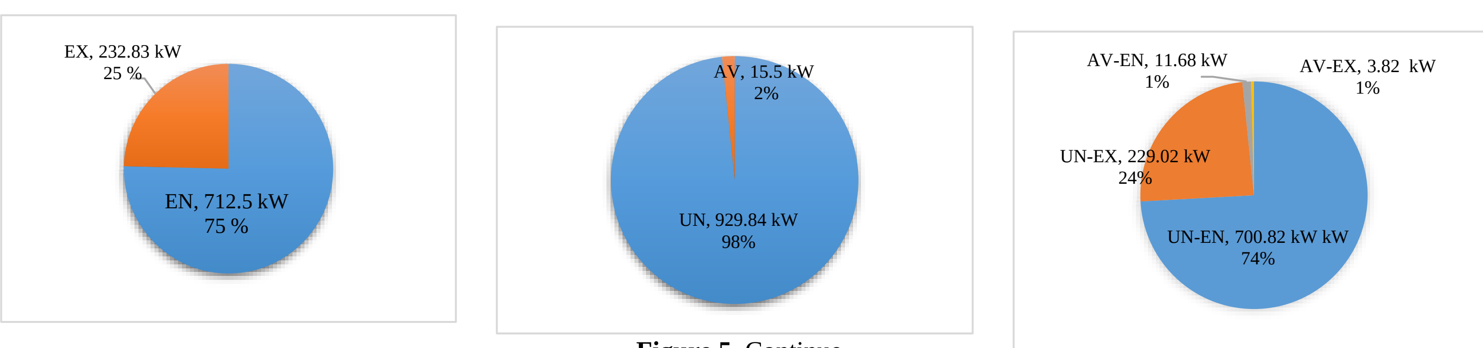
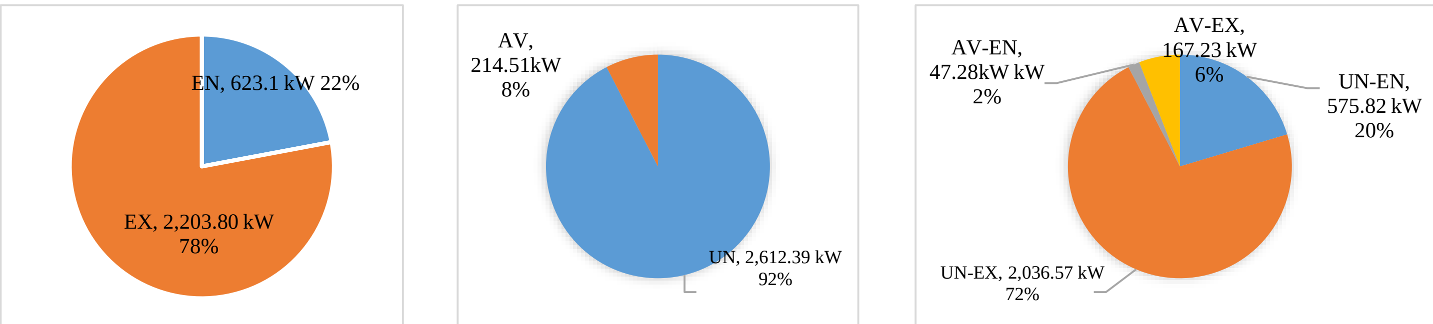


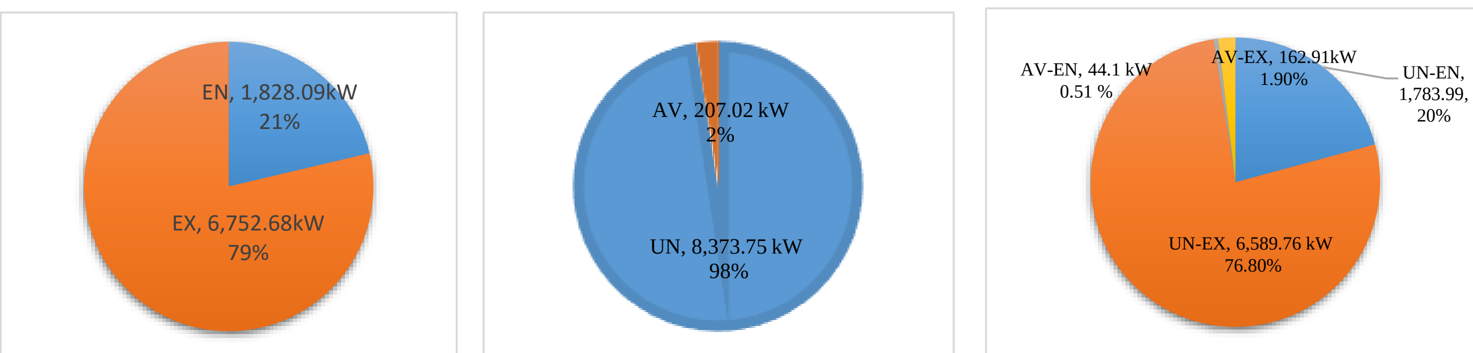
Figure 5. Continue

Parking plant (PP)

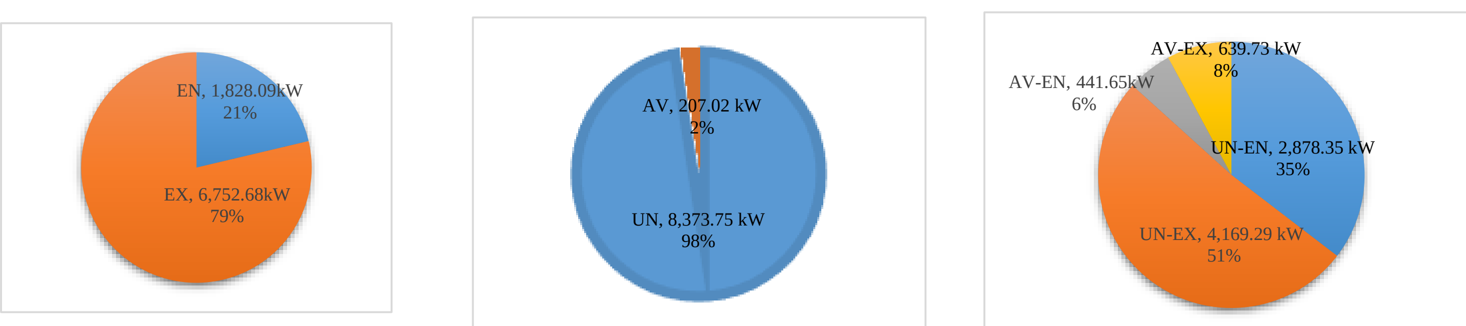
Crusher (CR)



Raw mill (RM)



Preheater (PH)



Rotary kiln (RK)

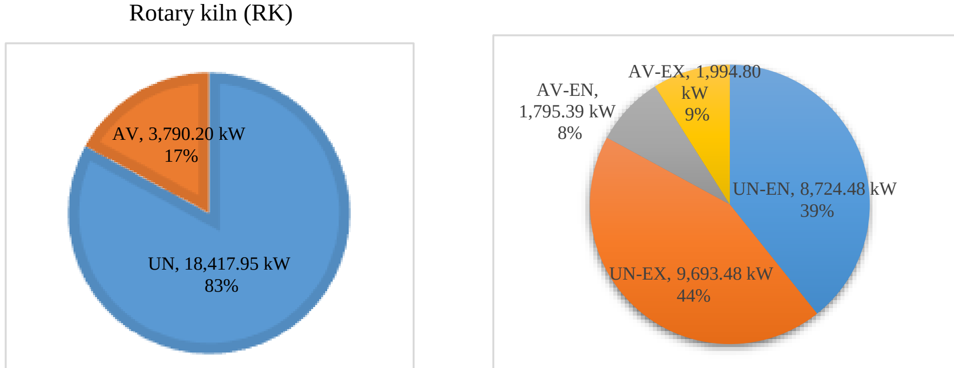
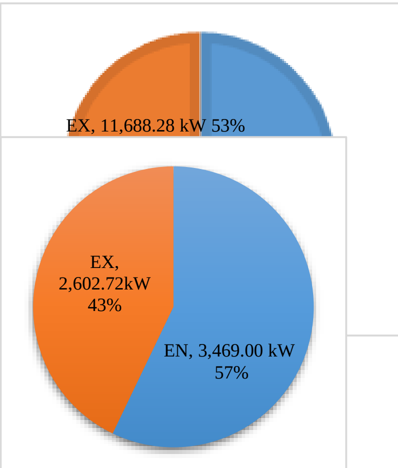
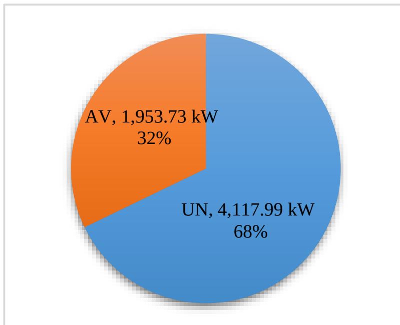
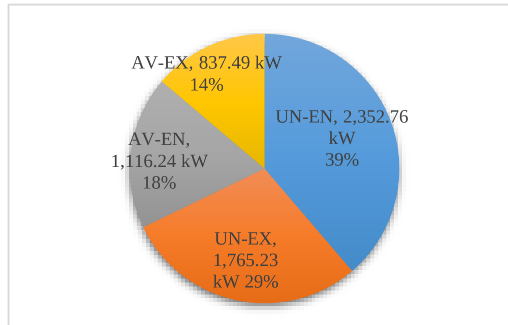


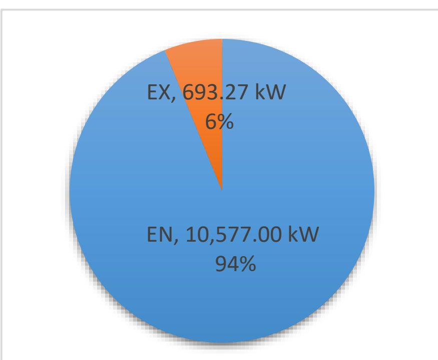
Figure. 6. The splitting the components system ED rate into Exogenous, Endogenous, unavoidable Clinker cooler (CC) nous-unavoidable, endogenous-avoidable, Exogenous-unavoidable and exogenous-avoidable parts for L2

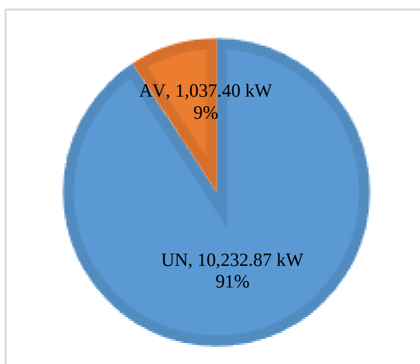


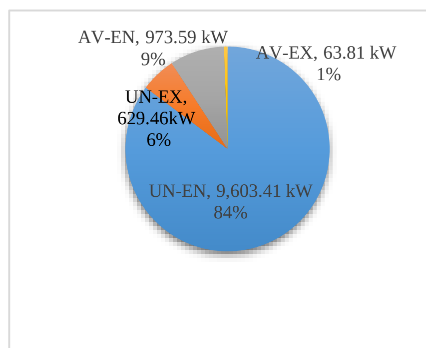


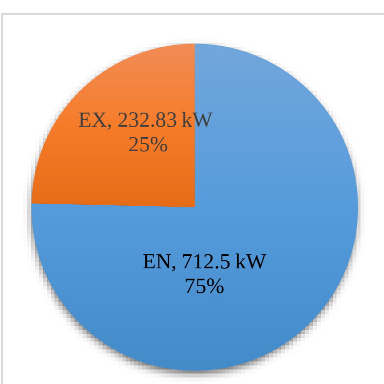


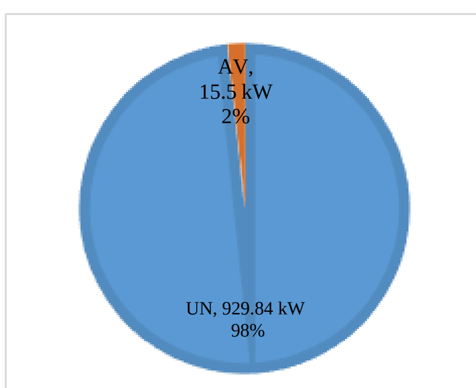
Cement ball mill (CBM)











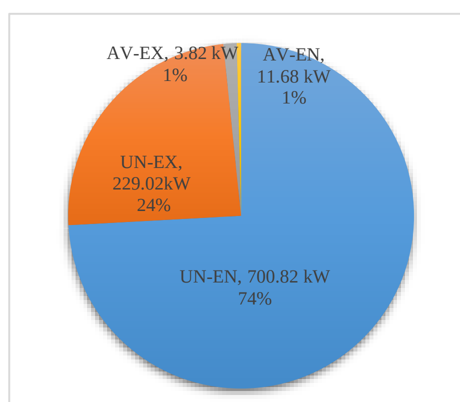


Fig. 6. Continu

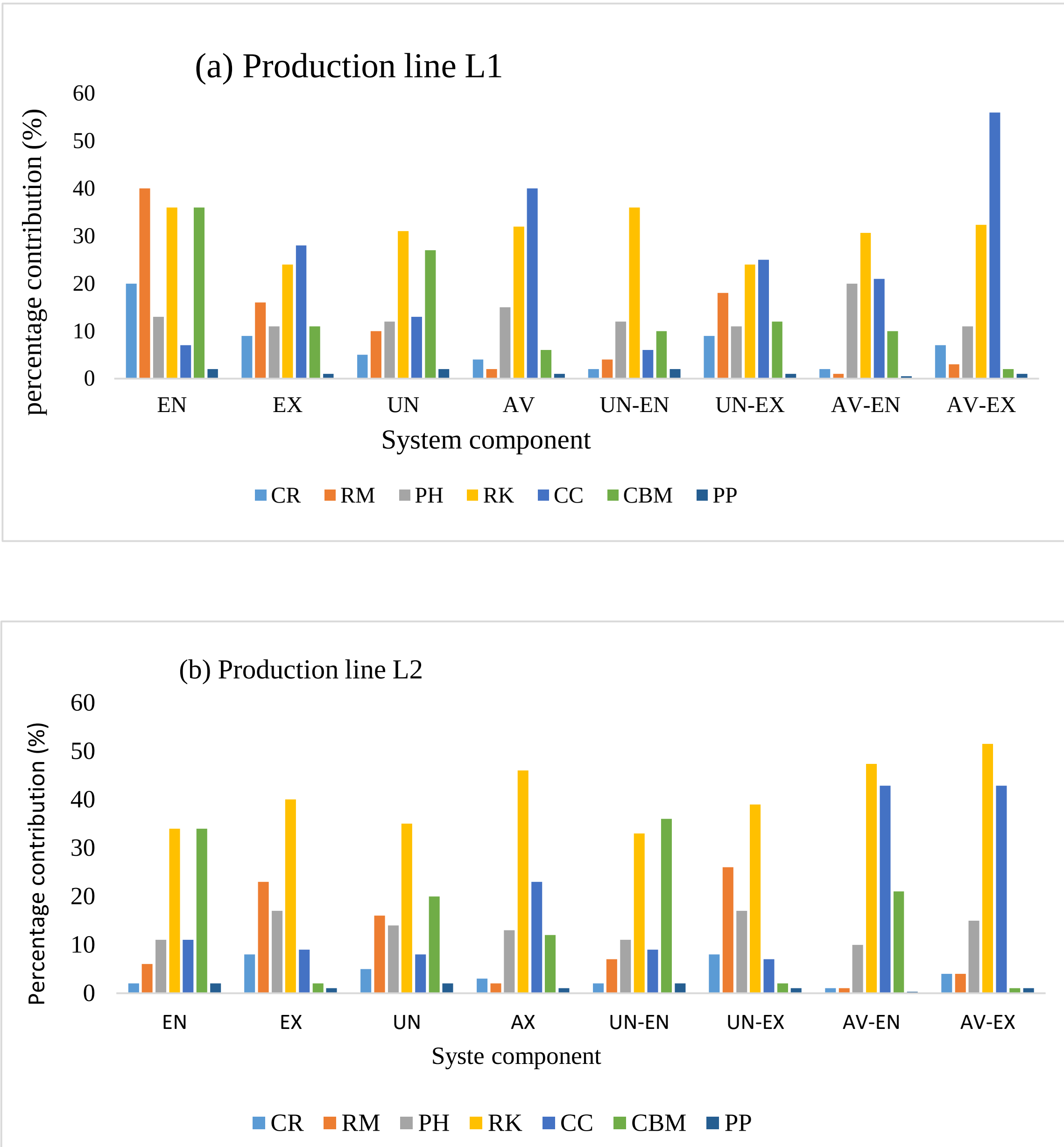


Figure 7. The contribution of the different components system in the overall Exogenous, Endogenous, unavoidable, avoidable, endogenous-unavoidable, endogenous-avoidable, Exogenous-unavoidable and exogenous-avoidable ED rate (a) production line L1 (b) Production line L2

Conventional exergy-based analyses

Figure 3. presents the overall exergy efficiencies and the exergetic variances of the L1 and L2. The efficiencies were calculated at 58.22 % and 55.58 % respectively. The exergy of fuel (EF), exergy of

production (EP) and exergy destruction (ED) ranged between $135.16 \leq \text{EF} \leq 135.29$ MW, $75.13 \leq \text{EF} \leq 78.77$MW and $56.52 \leq \text{ED} \leq 60.03$ MW in that order. However, a variance of 3.51MW in the total rate of ED for L1 and L1 was observed, with L2 having the highest ED, of 3.64 MW loss in EP.

DISCUSSION

Conventional exergy-based analyses

Comparing components losses and efficiency, (Figure 3), the highest ED in the production lines occurs in the rotary kilns. This is attributed to the energy required for drying the raw meal, calcination, and clinkerization, as well as the corresponding power needed to drive the kiln and its sub-components. The ED in the cement milling units was next to the rotary kilns calculated at 14.30 MW for L1 and 11.27 MW for L2. The reason is the high energy requirement to start and sustain the mills. The L1 ball mills was less efficient than Line 2, with ED rate of 14.44% and 29.91%, respectively. This justifies the investment in the vertical cement mill for L2 having significant energy conservation.

Other components with high ED include the preheater cyclones tower unit and the vertical roller mills. The EE of the vertical roller mills in L1 and L2 were calculated at 64.45% and 53.37% with corresponding ED ratios of 7.03% and 7.27% respectively. The ED rates and efficiencies for the clinker coolers were estimated at 8.86MW and 6.07 MW (L1) and 64.44% and 77.28% (L2). Further analysis reveals that the ED ratios of each clinker cooler represent 11.87 % and 15.28% of the overall ED in each production line caused by associated product irreversibilities.

Conventional exergoeconomic-based analyses

The data available for the kiln shows that $\dot{C}_{D,k}$ is low, with 296.40 \$/h (L1) and 825.20\$/h (L2). The low $\dot{C}_{D,k}$ in (L1) is because the exergy loss at the kiln is used in the vertical roller mill (VRM) for drying and in the preheaters for precalcination, which reduces the duel time of the raw mill during clinkerization. Furthermore, for L2, the two inline 5 stages cyclone system gives the raw mill a better surface area and good heat exchange. The latter is responsible for precalcination and clinkerization, reducing the duel time and thus the ED.

Advanced exergy analysis for the cement plant

The result of the advanced exergy analysis implies that the two production lines have different component efficiency patterns, which may be ascribed to technological design. From Tables 4 and 5, since $\dot{E}_D^{EN}$ dominates it means that the significant part of ED originates from the internal irreversibilities of the components. Which suggest the design improvement should be tailored towards reducing the internal irreversibilities in the components. From the two production lines, CR CC and RM and CR, RM and RK had greater values of $\dot{E}_D^{EX}$, which also suggest the modification of other components to reduce ED.

The technical modifications of RK and CMB, which constitute over 30 % and 27 % of $\dot{E}_D^{UN}$ for L1 and 35 % and 19.78 % for L2 is imperative as this will improve component efficiency. It is evident that the $\dot{E}_D^{UN}$ in a cement production plant is inevitable; however, waste energy from a component like RK could be harnessed.

Separating the Components' Exergy Destruction rate

From Figure 7a, the avoidable exogenous ED is highest for the CC (56.86%) of the overall components and 20.11% for the L1, followed by the RK having 32.35% at the component level and 19.88 % for the L1. Equally, the highest avoidable exergy endogenous ED occurs in the RK with 30.65% at the component level and 15.23% contribution to the total in L1. The PP have the lowest contribution of avoidable endogenous (0.52%) and exogenous (0.16%). From Figure.7b, the highest avoidable exogenous ED exist in RK and account for 52.63% at the component level contributing about 51.55% to the total in L2, followed by the CC (42.87%) at the component level and 21.64% of the total for L2. Also, the highest avoidable exergy endogenous ED occurs in the RK (47.37%) at the component level and 40.53% compared to the total for the L2 components. The PP is found to have the lowest contribution of avoidable endogenous (0.26%) and exogenous (0.10%).

Implication to Research and Practice

This study provides significant update of upgrading potentials and cost improvement. It is critical, to identify and assess results to avoid additional environmental problems or needs. The data presented in this research would be applied to comprehend improvement potentials in the design of cement plant to reduces the avoidable exergy destruction and the attendant cost implications. It also provides insightful directives on the interactions of process and economic concerns, and approaches to optimize the overall processes and performance of the cement plant.

CONCLUSION

The study presents an all-inclusive advanced exergy and exergoeconomic, analysis of a cement production plant. The research was based on splitting the ED into exogenous, endogenous, avoidable, unavoidable, exogenous-unavoidable, exogenous-avoidable, endogenous-unavoidable, and endogenous-avoidable made the study novel as available studies in a cement plant was based on conventional applications. The results are summarized as follows:

1. The components with the highest exergetic efficiency (EE) include the PH (78.96%), CR (74.39%) and CC (64.44%) for L1 and the CC (77.28%), CR (74.39%), and PH (71.32%) for L2 respectively
2. The majority of the ED of the plant was found to be endogenous (54.74%) and unavoidable (88.85%). Potential improvement rests on improving the internal operating parameters of the components (endogenous ED). In contrast, component interfaces (exogenous ED) are insignificant comparatively. The total avoidable ED consists of the ED caused by each component to itself (endogenous) and to the plant's remaining components (exogenous). The

outcomes are comparable to conventional analysis: the CC and RK L1 and L2 improvement priorities are ranked highest.

3. The overall ED cost for L1 and L2 was $24,788.77/h and $26,403.50/h. Based on the lowest ED cost, L2 is preferred. The PHs account for 51.0% and 47.71% of the respective overall ED cost for L1 and L2. Thus, upgrading the PHs for related cost improvement potentials is imperative.

This research is unique as it applies advance exergy and exergoeconomics to a local cement plant in Mfamosing, Nigeria using instantaneous operating parameter to show the actual state and economic valuation of the cement plant. The results express the true state of the plant and gives the management a perspective for improvement and reduction in the cost of exergy destructions that occurs at component levels. It also calls for further studies in the cement industry towards identifying the avoidable sources of exergy destruction and the corresponding economic effects as studies on this subject in this cement industry are very limited.

Future Research

Further research is required to investigate the causes of the unavoidable endogenous exergy destruction and convert it to other forms of energy that can be utilized by the component and the plant in general. A reduction of the “unavoidable” exergy destruction will present potentials for system and process improvement.

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