International Journal of Engineering Research and Development
e-ISSN: 2278-067X, p-ISSN: 2278-800X, www.ijerd.com
Volume 7, Issue 12 (July 2013), PP. 25-32

Exergoenvironmental Evaluation of a Cement Manufacturing Process in Nigeria

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Abstract:- The Cement manufacturing process is an energy intensive and environmentally impacting process. In this study, an exergoenvironmental evaluation is conducted on a wet process, gas – fired 1.3 million tonne capacity cement plant in Nigeria, to assess the ecological impact of its production process by revealing the extent to which each major component of the production process is responsible for the overall environmental impact and identify the sources of the impact.

Exergoenvironmental evaluation consists of three major steps. The first step involves a detailed exergy analysis of the production system under consideration using the input – output energy analysis method; in the second step, the required values of the environmental impact are determined by applying the ECO – 99 life cycle assessment method. In the third step the environmental impacts are assigned to the exergy streams in the process. Subsequently, exergoenvironmental variables are calculated and the exergoenvironmental evaluation is carried out.

Based on a 70% utilization capacity, embodied energy intensity of 7.07GJ/t and overall exergic efficiency of 0.55; the exergoenvironmental evaluation shows that the major process components impacting the environment were the kiln and limestone extraction processes. The study also showed that exergy destruction occasioned by process and combustion emissions in the kiln is the major source of environmental hazards in the process.With an overall environmental factor of 20.3% for the plant, the study concludes that the environmental hazards are mainly due to system irreversibilities in the process and not the related components environmental factor.

Keywords:- Exergoenvironmental analysis, Cement Manufacturing, Nigeria

I. INTRODUCTION

Exergoenvironmental analysis is an exergy based method that is used for designing and optimizing environmentally effective energy conversion processes. It is based on the idea that exergy analysis is the only rational basis for evaluating the true thermodynamic value of an energy carrier, the real thermodynamic inefficiencies in an energy system and estimation of the variables that unambiguously characterize the performance of system (or one of its components) from the thermodynamic view point.

The methodology is based on the thermoeconomic analysis and exergy as a comparative element to calculate the environmental impact of energy, transport and system inefficiencies (Tsatsaronis, 1985). The methodology is applicable to any energy conversion process and takes into account the environmental and energy interactions between various components of a system and allocates the impacts of exergy streams. However, unlike the exergy allocation in which the plant is analyzed as a black box, the exergoenvironmental allocation requires taking into account the different processes within the plant and equipments where irreversibilities are produced (Gonzalez et al, 2002)

This methodology has been applied to various energy conversion systems including power plants (Estibaliz et al, 2010), SOFC systems (Meyer et al, 2009), Refrigeration and air-conditioning systems (Tsatsaronis, 2010) and Electricity production systems (Buchgeister et al, 2010). In this study, the exergoenvironmental analysis has been applied to a 1.0 million metric tonne, wet – process cement plant in Nigeria. The cement plant produces mainly Portland cement and currently provides about 40% of local cement production in Nigeria.

II. THE METHODOLOGY OF EXERGOENVIRONMENTAL ANALYSIS

An Exergoenvironmental analysis consists of three steps: an exergy analysis, a Life Cycle Assessment (LCA) of the components of the system and their environmental impact and an exergoenvironmental evaluation (Meyer et al, 2009). This method is the counterpart of the exergoeconomic analysis, but instead of using economic costs in the balance of each component, environmental burdens are quantified.

2.1 Exergy Analysis

The first step in the exergy analysis is the definition of the system boundaries and the components considered in the study. The exergy analysis of the system is then determined by evaluating the exergy of the different components and flows in the system. After that the exergy flows and exergy content of all the components are determined. The exergy flows are calculated as the sum of the physical and chemical exergy while the kinetic and potential exergy can be rejected.

In an exergy analysis each component is characterized by an exergy of product $\dot{E}_p$ and an exergy of fuel $\dot{E}_f$. The product and fuel definition depends on the exergetic purpose of the different components. (Lazzaretto et al, 2006; Szargut, 1980). After calculating the exergy of fuel and exergy of product, the remaining exergetic variables can be calculated for each system component (A. Bejan et al, 1996). This includes the exergetic efficiency and exergy destruction.

The exergetic efficiency is defined as the ratio between the exergies of product and fuel (Grassman, 1950).

$$\varepsilon = \frac{E_p}{E_f} \qquad (1)$$

Exergy destruction $\dot{E}_D$ is the direct measure of the thermodynamic ineffiency. It is calculated as:

$$\dot{E}_D = \dot{E}_f - \dot{E}_p \qquad (2)$$

Furthermore, the exergy cost of the system flows can be obtained as the inverse of exergetic efficiency. Exergy cost of a stream is the quality of exergy resources that is necessary to be consumed in order to produce the stream.

$$\kappa = \frac{\dot{E}_f}{\dot{E}_p} \qquad (3)$$

The percentage of exergy destruction $\dot{Y}$ compares the exergy destruction in the component analyzed with the exergy destruction in the entire system.

$$\dot{Y} = \frac{\dot{E}_{D,component}}{\dot{E}_{D,total}} \qquad (4)$$

2.2 Life Cycle Assessment (LCA)

In environmental analysis, an LCA of each input stream entering the overall system and of each component of the process carried out. The total system used to conduct the LCA includes the supply of the input streams, especially fuel and the full life cycle of components. Inventories of elementary flows (i.e. consumption of natural resources and exergy as well as the emissions) are compiled following the guidelines of international standard approaches.

Based on the Life Cycle impact results, the environmental impacts are calculated for the various categories by a quantitative impact assessment. For the methodological development of exergoenvironmental analysis, a single – score life cycle impact assessment (LCA) method, ECO – Indicator 99 is chosen (Goedkoop, 2000). ECO – Indicator 99 is an LCA method that supports decision making in design for the environment. Besides the ECO – Indicator 99, other LCA methods exists, which are discussed in literature (H.A. Udo de Haes et al, 2002; Jolliet, O, 2004). A comparative investigation of exergoenvironmental analysis using ECO – Indicator 99, CML 2001 and Impact 2002 as LCA methods are discussed in (Buchester, J; 2010).

The ECO – Indicator 99 is obtained from the analysis of three damage categories: human health, eco system quality and natural resources. To calculate ECO – indicator 99 score three steps are carried out (Pre Consultants, 2001). First the inventory of all resources and emissions that constitute the life – cycle of the system is obtained, then the damage these streams cause to the three categories is calculated and finally, a weighted point of the three categories is applied. Inventory is a standard step in LCA.

2.3 Exergoenvironmental Evaluation

In this third step, the LCA results expressed in Eco – Indicator points are assigned to the corresponding exergy flows. This is done initially by determining the environmental impact rate B_j,which is expressed in Eco – indicator points per time unit (pts/s or mPts/s). This impact rate is calculated for each stream and its value is the product of the specific (exergy – based) environmental impact b_j, the average environmental impact associated with the production of the *jth*flow per exergy unit of the same flow (Pts or mPts/GJ exergy) and the exergy rate $\dot{E}_j$

$$B_j = b_j \cdot \dot{E}_j \qquad (5)$$

The environmental impact rate $B_j$can also be calculated using the specific exergy$e_j$and the mass flow rate $m_j$as:

$$B_j = b_j \cdot m_j \cdot e_j \qquad (6)$$

Similarly, the environmental impact rate associated with heat *Q* and work *w* are calculated as follows:

$$B_q = b_q \cdot \dot{E}_q \qquad (7)$$

$$B_w = b_w \cdot W \qquad (8)$$

The exergy rate associated with a heat transfer is expressed as:

$$\dot{E}_q = \left(1 - \frac{T_0}{T_j}\right) Q \qquad (9)$$

Where T_0 is the surrounding temperature and T_j the temperature at which the heat transfer crosses the boundary of the system.
The environmental impact related to the system components is expressed as:

$$B_{o,k} = B_{i,k} + Y_k \qquad (10)$$

$$b_o \cdot \dot{E}_o = b_i \cdot \dot{E}_i + Y \qquad (11)$$

Where B_0 is the environmental impact of outputflows;B_i the environmental impact of input flowsand Y the component-related environmentalimpact.
The environmental impact of a component canbe also shown in terms of environmentalburdens of fuel (F), product (P) and exergylosses (L). When the F-P-L analysis is carriedout the following expression is obtained:

$$B_p = B_f - B_L + Y \qquad (12)$$

Where $B_p$is the environmental impact of products, B_F the environmental impact of fuels, Y is the component related environmental impact and B_L the environmental impact of the losses. When a component is analyzed, the environmental impacts of its input streams are always known, either because they are outputs of other components or because they are resources.

The values for internal and output flows can only be obtained by considering thefunctional relations among system components. This is done by formulatingenvironmental impact balances and auxiliary equations. The environmental impactbalance for the k-th component states that the sum of environmental impact ratesassociated with all input flows plus the component environmental impact rate isequal to the sum of the environmental impact rates associated with all outputflows.
The equation is

$$\sum_{j=1}^{n} B_{j,k,in} + Y_k = \sum_{j=1}^{m} B_{j,k,out} \qquad (13)$$

In this study, the hazard of losses is calculated as the product of the specific environmental impact of fuel and the exergy of losses $\dot{E}_L$. The environmental burdens of the fumes emitted by the kiln and the final grinding process of clinker and gypsum are supposed to be compensated by an additional consumption of fuel, so this impact is assigned to consumed fuel. The environment hazard due to losses $B_{l,k}$ is estimated as:

$$B_{lk} = -B_f - \dot{E}_l \qquad (14)$$

The environmental impact of the exergy destruction in a process is the product between the exergy destruction and the specific environmental impact of fuel. It is necessary to consume more fuel to compensate exergy destruction. The environmental impact of fuel destruction is stated as:

$$B_{Dk} = -B_f - \dot{E}_D \qquad (15)$$

The LCA provide the environmental impact for each component, and it is made upof the three life cycle phases of construction (CO), operation and maintenance (OM),and disposal (DI). The sum of all component-related environmental impacts is $\dot{Y}_k$and is shown in equation 16

$$\dot{Y}_k = \dot{Y}_k^{CO} + \dot{Y}_k^{OM} + \dot{Y}_k^{DI} \qquad (16)$$

Within the analyzed system, the direct emissions from a component are assignedto the operation and maintenance phase. The construction phase includesmanufacturing, transport and installation of a component. The equation 13 ofthe environmental impact balance of a component cannot be solved if the numberof output flows, and therefore the number of unknown variables, is greater thanone.

All the environmental impacts of a componentare assigned to the product of that component.The exergoenvironmental factor $f_{b,k}$ shows whichthe principal source of environmental impactassociated with the considered component is. Ifthe value of this variable is nearly one therelated-components environmental impact is themost important source, whereas if this values isconsiderably lower than one, irreversibilities arethe principal source of impact.

$$f_{b,k} = \frac{\dot{Y}_k}{\dot{Y}_k + B_{D,K}} \qquad (17)$$

2.4 Treatment of dissipative components

In process operations, usually components without a productive or exergetic purpose are part of a system.Examples for this type of components, which are called dissipative components(DCs), are coolers, gas cleaning units, or throttling valves operating entirely orpartially above surrounding temperature. These components decrease the exergycontent of a flow without generating an immediate useful effect. A product fromthe thermodynamic viewpoint cannot be defined for these components, whichserve either other so-called productive components or the overall system directly (Fratzler et al, 1986).

The environmental impact due to thermodynamic inefficiencies within a DCand the component-related environmental impact should be charged to theproductive components or to the product of the overall system, if this system isbeing served directly by the DC. The approach for the calculation is given in (Lazzereto, 2006).

III. THE CEMENT MANUFACTURING PLANT

The selected cement manufacturing process is shown in the Figure 1 below. The cement plant under consideration is a wet process, natural gas fired kiln with a total installed capacity of 1.0 million metric tonnes of cement per annum. The cement plant has two units of operation in its quarry and crushing sections, three units of operation in its raw grinding or roller mill units, two units of operation in its calciner and kiln units and two units of operation in its finish grinding or cement mill section.

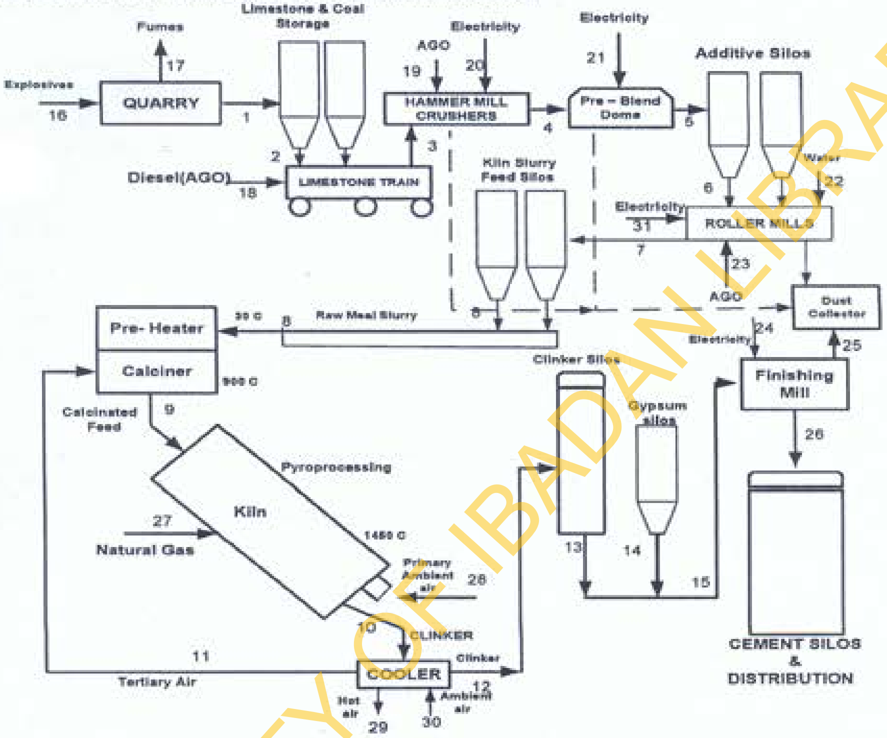

Figure 1: The Cement Manufacturing Process in the Selected Cement Plant.

From the figure it can be seen that there are six principal steps in the manufacture of cement. These are: quarrying, limestone crushing, raw milling, production of clinker, cement milling and cement bulking and packaging.

The major raw material for the production of cement, limestone is quarried by blasting the rock using two major types of explosives. The first or primary explosives dislodge the limestone rocks in large pieces, which are further reduced by secondary explosives. The dislodged and reduced boulders of limestone rock are transported by the use of limestone trains to the hammer mill where they are crushed.

The crushing process proceeds in the hammer mill in two stages, the first stage reduces the limestone boulders to between 60 and 20mm in size, while the secondary crushing process further reduces the limestone fragments to less than 0.2mm in size. The materials are then stockpiled in the additive silos after passing through the pre – blending dome where there is addition of other materials like clay to improve its overall quality of the raw material.

The raw milling is carried out in roller mills where the raw material is further grounded into powdery form in adequate quantity and suitable composition for sintering in the kiln. The fines of the raw mix that is the result of this process is specified in terms of the size of the largest particles, and is usually controlled to ensure that the mix is chemically homogenous. In this wet process plant, there is an addition of 30 – 40% of water to the raw mix to form slurry. The minimum moisture content of the slurry is determined by the maximum viscosity of the permissible for the pumping of the slurry

The major content of the cement raw mix is limestone ($CaCO_3$)obtained from the quarry which is between about 74 – 79% by mass and usually to improve the quality of the raw mix, the following oxides, which serve as composition correcting additives are also added; these are: silica SiO_2(17 – 25%) from sand or from fly – ash from coal combustion; Alumina Al_2O_3 (2 – 8%) from clay, shale or fly – ash from coal combustion and Iron Oxide Fe_2O_3 (0 – 6%) from iron ore or iron containing by – products.

The prepared raw mill is transferred to the pyroprocessing unit for the production of clinker from the kiln. This is the most vital operation in the production of cement. This process is very important for three reasons, firstly fuel consumption is the major expense, secondly, the capacity of a plant is measured by kiln output and the strength and other properties of cement depends on the quality of clinker produced.

The pyroprocessing system involves three stages: drying and preheating, calcining and burning or sintering stages. At the drying and preheating stage the raw mix is passed through a Precalciner where the raw mix is decarbonated and the temperature of the raw mix is subsequently increased to over 900^{0}C in the calciner. The calcined meal is now fed into the kiln were it undergoes a chemical transformation process to produce clinker.

The processes occurring in the kiln are the thermal decomposition of clay minerals, calcite, and eventually the formation of clinker at over 1450^{0}C. The clinker emerges from the kilnand passes into a cooler, where convective airflow cools it to a level suitable for subsequent handling and milling. The heat reclaimed from the cooling process is recycled to the kiln as secondary combustion air, while other gases reclaimed from the pre heater or Precalciner system are used as primary combustion air in the kiln.

Cement is produced by grinding the cooled clinker with gypsum (hydrated calcium carbonate). The grinding takes place in finishing mills. The ground cement is stored in large silos for distribution either in bag or bulk forms.

3.0 Results and Discussions

3.1 Exergy Analysis

The exergy analysis has been calculated under the following assumptions:

1. The reference temperature of the of the environment is set at 25^{0}C, while the reference pressure is set at 1 atm.
2. The radiation and convection losses in the process units have not been considered.

The exergy analysis of the cement plant was conducted for one year of operation and each of the major components of the plant shown in figure 1 has been considered separately in the exergy analysis and exergoenvironmental analysis. The calculation of the exergetic efficiency of the components is based on the definition of exergetic fuel and exergetic products shown in Table 1.

Table 1: Exergetic Variables of the system

System Component	Exergetic Fuel $\dot{E}_f$	Exergetic Product $\dot{E}_p$	Exergetic efficiency (%)	Exergetic Destruction $\dot{E}_D$(GJ)
Quarry	$\dot{E}_{16}$	$\dot{E}_{16} - \dot{E}_{17} = \dot{E}_1$	95	2051.4
Limestone Train	$\dot{E}_{18}$	$\dot{E}_{18} - \dot{E}_{31}$	90	77.1
Hammer Crushers	$\dot{E}_{19} + \dot{E}_{20}$	$\dot{E}_4$	86	0.0
Roller Mills	$\dot{E}_{31}$	$\dot{E}_7$	73	0.0
Calciner	$\dot{E}_{11}$	$\dot{E}_9$	80	0.0
Kiln	$\dot{E}_{27} + \dot{E}_9$	$\dot{E}_{10}$	48	359655.6
Finishing Mill	$\dot{E}_{24}$	$\dot{E}_{26}$	68	0.0

According to the results of the analysis, the overall exergy efficiency of the process is 55%, which is considerably lower than the overall energy efficiency of the process with a value of 78%. The results also show that the kiln is responsible for over 95% of the destroyed exergy within the process. Other major components that contributed a small fraction to the inefficiency of the process are the limestone train and the quarrying equipment.

A total of 361784 GJ of exergy is destroyed within the process and in addition, a significant amount of 374 GJ of process – based and combustion – based CO_2 emissions were released into the environment.

3.2 Life Cycle Assessment

Table 2 and figure 2 shows the environmental impact values for a year of production. The sum of the environmental impacts of all the flows and all the components has being assigned to the different products. The total environmental impact for the annual production of the year under consideration of 700,000 tonnes of cement is 676points.

Table 2: Environmental Impacts of Input Streams and System Components For Cement production

s/n	Item	Eco - Points
Input Streams		
1.	Extraction of Limestone	257
2.	Electricity	0.014
3.	Natural gas	231
4.	Extraction of Shale	0.002
Process Equipments		
5	Quarry Equipment	1.42
6.	Limestone Train	12.8
7.	Hammer Crushers	0.0
8.	Roller Mills	0.0
9.	Calciner	0.0
10.	Kiln	172
11.	Finishing Mill	1.38
	Total	**675.5**

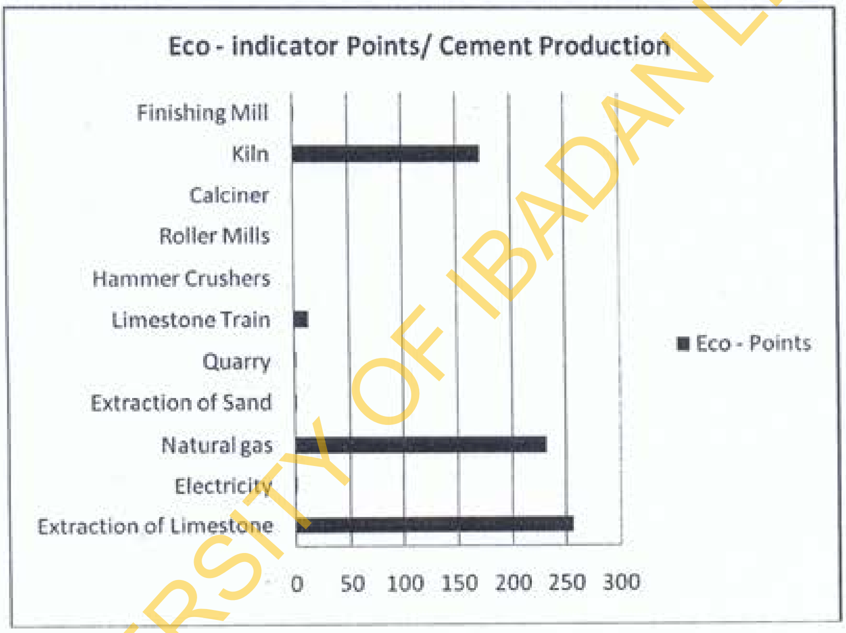

Figure 2: Eco – Indicator for Selected Cement Plant in Nigeria.

The highest environmental impact of about 38% is that of the extraction of limestone because the environmental impact of the direct CO_2 emission associated with the process is included. Other high contributions to the environmental impact are made by the natural gas used in the pyroprocessing stage of cement production followed by the kiln, which is the major equipment for the production of clinker which is the most important process in cement production.

The result clearly shows that the LCA results for the upstream processes of input streams (limestone extraction and natural gas), as well as the kiln are the major areas for optimization in the design for environment of cement processing equipments.

3.3 Environmental Analysis

In order to estimate the environmental cost of each of the flow stream in the cement manufacturing process, 7 sets of equations have been developed to describe the flow of energy and material of the system.

Flow1, 10 and 28 represents the major products of the system. The exergoenvironmental balance equations applied to each one of the system components and the environmental analysis of results of the system components are shown in Table 3.

Table 3: Exergoenvironmental Balance of system Components

s/n	System Components	Exergoenvironmental Balance	Y_k (mPt/s)	B_k (mpt/s)	B_{TOT} (mpt/s)	F_k
1.	Quarry	$B_{16} - B_{17} + \dot{Y}_1 - B_1$	0.477	2.913	3.39	0.14
2.	Limestone Train	$B_{18} + B_2 + \dot{Y}_2 - B_3$	0.014	0.987	1.001	0.014
3.	Hammer Crushers	$B_{19} + B_{20} + B_3 + \dot{Y}_3 = B_4$	0.0	0.0	0.0	0
4.	Roller Mills	$B_{31} + B_6 + B_{22} + \dot{Y}_4 + B_{23} = B_7$	0.0	0.0	0.0	0
5.	Calciner	$B_8 + B_{11} + \dot{Y}_5 = B_9$	0.0	0.0	0.0	0.0
6.	Kiln	$B_9 + B_{27} + B_{28} + \dot{Y}_6 = B_{10}$	7.1	137	144.1	0.049
7.	Finishing Mill	$B_{24} + B_{15} + \dot{Y}_7 = B_{26}$	0.0	0.0	0.0	0

The cement plant under consideration, for the specific year considered had a total annual production of 692655 tonnes of cement and 606,562 tonnes of clinker respectively. The total exergy input into the process was 3,373,096 GJ and energy input of 4,648,571 GJ. The embodied energy intensity of cement production for the year was 7.07GJ/tonne.

The resource consumption in the entire system (exergy GJ/year) is the sum of the natural gas burned in the kiln equipment, the electricity supplied to all the equipments in the plant, and the volume of explosives used in the extraction of the limestone, as well as the diesel fuel used to power the limestone train from the quarry to the crusher and mills. The natural gas consumed in the kiln for one year of operation is 4,225,501GJ, while the electricity supplied to the entire process for the year was 307,778 GJ or 85,494 Mwh. Total fuel consumed in the limestone train was 99,877 GJ and the volume of explosives used in the quarry was 1702 GJ.

The sum of all the environmental impacts of components life cycle and input streams in the entire system, represents the impact – related to the final products. To allocate the overall environmental impact it is necessary to consider all the exergy products obtained from each product.

The production of both limestone and cement respectively caused an overall impact of 3390 pt/year and 144100pt/year respectively. The results also show that the exergy destruction occasioned by process and combustion emissions in the kiln is the major source of environmental hazard in the process. The overall environmental factor for the plant is 20.3%, which also shows that the environmental hazards are mainly due to system irreversibilities in the process and not the related components environmental impact.

Hence to achieve the goals of design improvement for the process under study, the process has to be redesigned to minimize the cumulative environmental impacts of the process flows at the kiln. A reliable improvement of the overall energy conversion process with respect to ecological aspects can only be realized if the exergy of the exhaust gases from the kiln can be used in additional ways to optimize the process or to supply heat to any other process ancillary to cement production such as the production of hydrated lime, which is used for water purification.

The exergoenvironmental analysis has further shown the potential of optimization more in details and reveals the influence of the components among themselves than is possible with an LCA. Particularly of interest is the fact that the high environmental impact rate of the kiln due to the high exergy destruction is revealed.

IV. CONCLUSION

An exergoenvironmental method has been proposed that has investigated the formation of environmental impacts of the cement production process, which is a major energy conversion and environmentally impacting process. The environmental impact of cement production has been assigned the exergy flows in the analyzed production system. There are basically two sources of environmental impacts which were identified as associated with the process components: thermodynamic inefficiencies and impacts associated with the life cycle of the components.

The exergoenvironmental analysis of the cement production process showed that the exergy destruction occasioned by process and combustions emissions of the raw meal in cement production and the natural gas burned in the kiln has the highest impact followed by the limestone extraction process. The analysis also showed that the calciner, hammer crushers and roller mills are the most environmentally relevant components of the system.

The exergoenvironmental analysis has also shown that the effects of exergy destruction within a component on the formation of environmental impacts depends on the position of the component in the process because the exergy rates provides the unified basis of interrelationship between the components, which is why the exergoenvironmental analysis provides more helpful information of the design for environment than a pure LCA.

Furthermore, it would be interesting to combine the exergoeconomic and exergoenvironmental analysis in order to obtain a suitable and powerful tool approach to achieve a thermodynamic, economic and environmental performance of the cement production process.

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