Energy or Material Savings? Exergy replacement cost applied to a thermoeconomic analysis of three different resource-intensive industries

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Abstract

Thermoeconomics is largely used to assess industries where energy flows come into play. However, how could material flows be assessed? Conventional exergy analysis uses chemical exergy, but it does not reflect their industrial value. Exergy Replacement Cost (ERC) is proposed to evaluate the material resources that come from natural deposits. It is a novelty with respect to the conventional exergy analysis that allows to assess material efficiency in industries in a fairer way. Material and energy efficiency must be optimized, because there are scenarios where material savings increases, but the energy ones decreases. This paper is focused in the application of ERC concept to a thermoeconomic analysis of three resource-intensive industries, such as a cement plant, a fertilizer factory and a ceramic production plant. It has been demonstrated that material efficiency can be assessed fairly in this way. The existing parameters of the industries have been proposed as the reference case. New scenarios have been analyzed so as to study the potential for improvement in terms of exergy consumption with respect to the reference case. These exergy savings are related to both energy and non-energy sources.

Keywords: Cement, Fertilizer, Ceramic, Exergy, Exergy Replacement Cost, Resource-intensive industries, Resource consumption, Thermoeconomic analysis, Thermoeconomic diagnosis.

1 Introduction

Thermoeconomics has a large potential for optimization in industries. Conventionally, it has been used in order to evaluate energy systems [1, 2, 3, 4]. However, how could non-energy flows be assessed?

Traditionally, non-energy flows have been evaluated by means of chemical exergy. It has already been demonstrated that chemical exergy assesses only partially the physical value of materials [5]. Chemical exergy analysis of this type of flows is usually negligible in comparison with the exergy of the energy flows. For instance, the chemical exergy of limonite is 300 times lower than the petroleum coke one. Therefore, the contribution of non-energy flows is usually negligible with this type of analysis. Additionally, chemical exergy do not reflect their industrial value. For instance, the chemical exergy of petroleum coke is 100 times greater than the gold ones, but the cost of gold is not 100 times lower than the cost of the pet coke. Accordingly, conventional analysis does not take into account other important features of minerals, such as their scarcity.

How could this problem be solved? We propose to use Exergy Replacement Cost (ERC), accounting for the concentration exergy that raw materials have with respect to a complete dispersed state [6]. Accordingly, a very abundant and concentrated mineral such as limestone in the crust has a low exergy replacement cost, whereas a scarce one such as fluorite has a high one [7]. The application of ERC in industries in order to assess their material efficiency is a novelty that is explained in this paper. It provides a fairer value to non-energy resources. Additionally, ERC allows to allocate cost among non-energy flows in a rational way. This analysis generates some questions: What is better? to improve energy efficiency losing valuable materials or to improve the material efficiency at the cost of losing energy efficiency. Energy or material savings? It is necessary to find an optimum between both. This optimum can be found by means of the application of ERC in industries that accounts an intensive resources consumption.

In this paper, ERC methodology has been applied in a thermoeconomic analysis of three different resource-intensive industries. These industries are a cement plant, a fertilizer factory and a ceramic production plant. It has been demonstrated that material efficiency is calculated in a fairer way than the conventional method. Additionally, different scenarios that assess raw material savings in terms of exergy can be evaluated by means of the application of ERC into the analysis. Otherwise, there are not any exergy difference between a ton of raw material from waste or from a quarry applying the conventional exergy analysis. However, the environmental benefit of using co-products from other industries or processes is obvious in comparison with the use of raw materials from quarries.

2 Materials and Methods

To carry out a thermoeconomic analysis, the first step is to know the processes that have to be studied. In case of this paper, a cement plant, a fertilizer factory and a ceramic production plant were assessed.

The second step was the exergy analysis of the system in order to calculate the exergy of each flow, which were defined in the previous step.

The last step was the thermoeconomic analysis of the system, where unit exergy costs of each process were calculated among other parameters. Processes which were characterised by having high unit exergy costs were the less efficient. Several scenarios could be assessed by means of a thermoeconomic diagnosis of each plant and their exergy savings, both material and energy, were calculated.

2.1 Studied industries

The studied industries account a high energy and raw material consumption but they have different productive processes. A brief description about the industries has been done on the next sections.

2.1.1 Cement plant

The cement plant configuration is shown in Fig. 1. Limestone and marl is transported to the cement plant from quarries. It is crushed in order to reduce its size. By means of feed bins, limestone, marl, sand, limonite, fluorite and gypsum is introduced into the raw mill where raw materials are homogenised and crushed. Raw meal is introduced into a cyclone preheater in order to increase the temperature and a partial calcination is carried out. The preheated meal enters the rotary kiln in order to complete its calcination process. Calcined meal leaves the rotary kiln after passing through the cooling system, which is an integral part of the kiln. This product is known as clinker. The clinker can be a product of the factory or it can be milled with other materials, like fly ashes or gypsum, in order to produce cement.

The studied cement plant uses petroleum coke, biomass and solid recovered fuel (SRF) as fuel. Biomass and SRF meet the size specifications but petroleum coke has to be milled. This milling process needs heat which is produced by means of a fuel burner.

The exhaust gases from the kiln are introduced into the cyclone preheater in order to carry out a partial calcination of the raw meal. A portion of gases from the cyclone preheater are introduced into the raw mill before being discharged through the exhaust stack in order to dry the raw meal. The exhaust gas temperature is reduced and the particles are removed through filter sleeves before being introduced into the exhaust pipe.

2.1.2 Fertilizer factory configuration

As it can be seen in Fig. 2, the fertilizer production plant uses three raw materials. They are phosphoric acid (H_3PO_4), calcium carbonate ($CaCO_3$) and particles of product that don't meet the minimum size specification. Raw materials come together in the mixer, where calcium phosphate ($CaHPO_4$) is formed.

$$H_3PO_4 + CaCO_3 \longrightarrow CO_2 \uparrow + CaHPO_4 + H_2O$$

The granules of calcium phosphate account a high humidity, so it is necessary to dry it. A natural gas boiler is used to produce gases with a temperature of 450 ^{o}C that will reduce the humidity of the granules. It is necessary to cool the

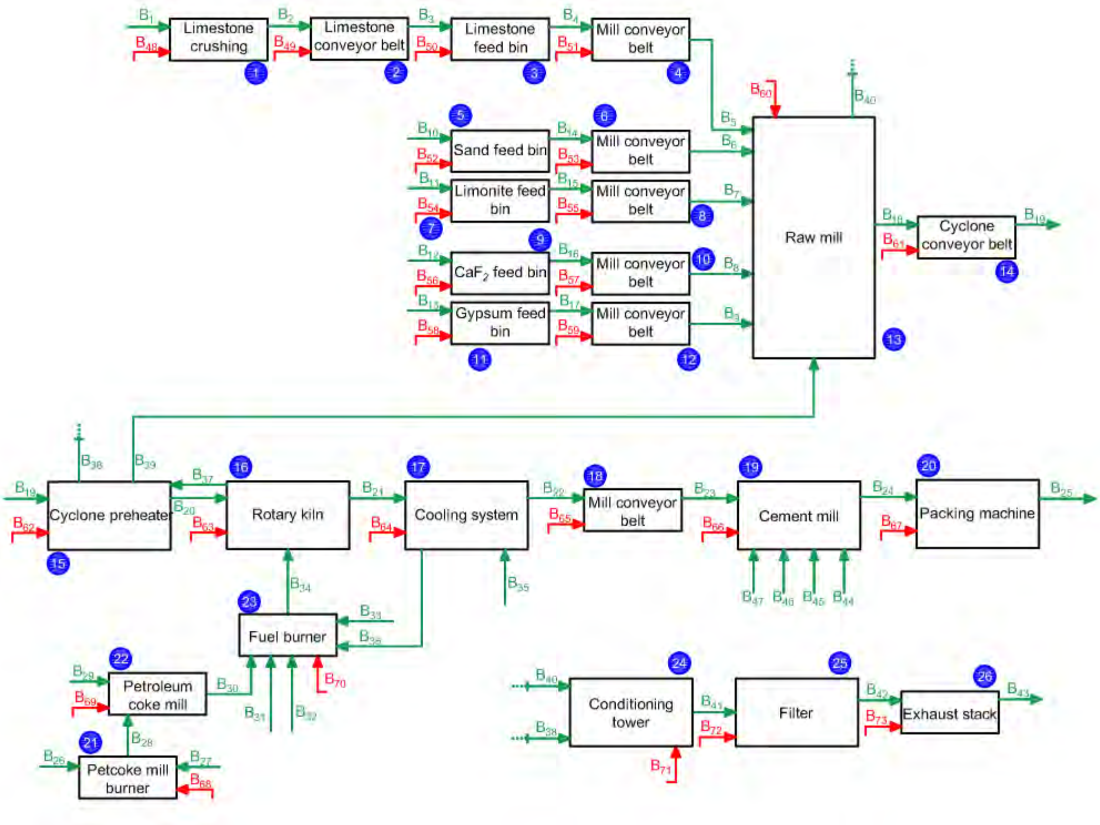

Figure 1. Process flow diagram of the studied cement plant.

product of the dryer in order to be introduced in the sieve. A size classification is done in this stage. The granules are divided in three categories:

- Undersized granules: Granules that do not meet the minimum size specification ($200\mu m$) are recirculated to the propeller in order to be introduced with the raw materials into the mixer stage.
- Great size granules: Granules that exceed the maximum size specification ($600\mu m$) are introduced in a mill in order to reduce their size. The reduced granules are introduced into the sieve again.
- Final product: Granules that meet the size specification ($200-600\mu m$) are considered as final product.

We can seen in the flow diagram dissipative processes. They are introduced due to there are some emissions of gases like CO_2 in the mixer or exhaust gases in the dryer.

2.1.3 Ceramic production plant configuration

The ceramic process starts with the grinding stage, as the flow diagram shows in Fig. 3. In this stage, the raw materials (Chamotte, clay, rubble...) are milled and stored in silos. They are mixed and homogenised before being introduced into the extrusion stage. The ceramic products are pre-formed in this stage.

The pre-formed tiles account a humidity of 16%. Therefore, it is necessary to decrease the humidity grade until 1%. In order to achieve this humidity grade, the tiles are introduced into four drying chambers, the detoning chamber, tunnel dryer, chamber dryer and heating chamber. All of the drying chambers are fed by means of gases from the cooling process except the heating chamber. The tunnel dryer, chamber dryer and heating chamber have natural gas burners. However, the burners of the tunnel dryer and the chamber dryer are used only if there are not enough heat from the kiln.

If the humidity of the paste meet the technical specification, it will be glazed. The glazing stage uses a large quantity of water. However, the biggest part of the water used is recovered. The last step of the process is the firing. The tiles are fired into a natural gas kiln at 1275 ^oC. Then, the tiles are cooled to finish the production process.

The process has several dissipative processes where the gases are emitted to the environment.

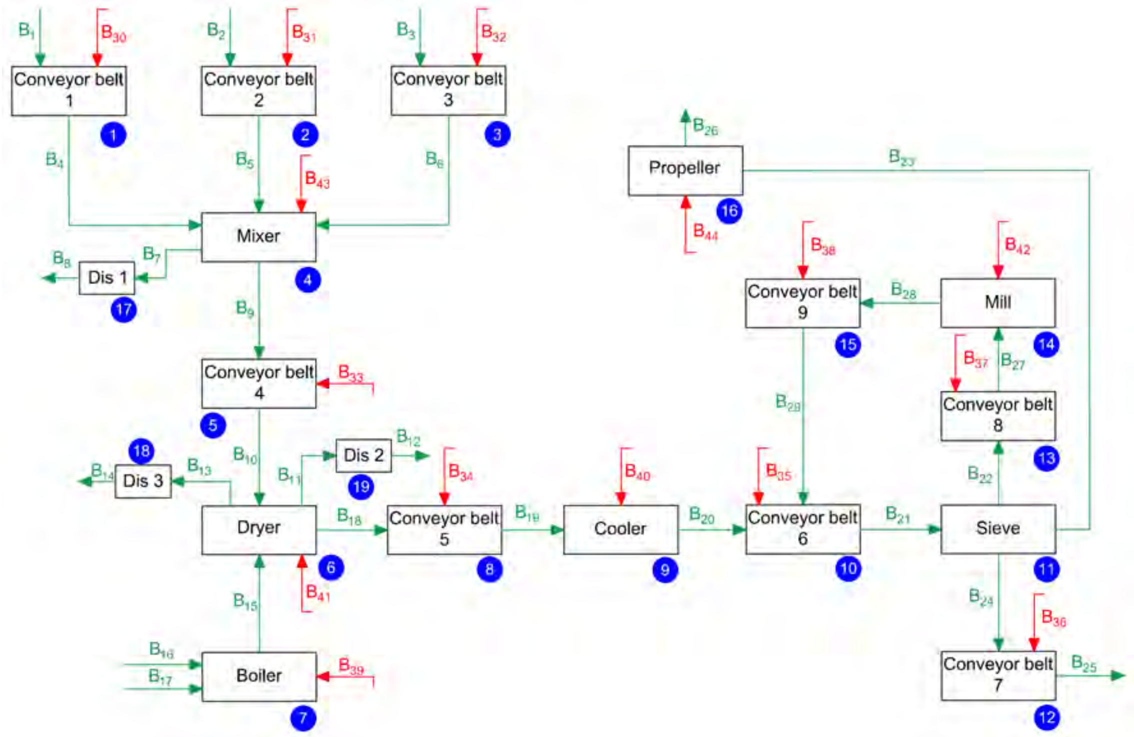

Figure 2. Process flow diagram of the studied fertilizer factory.

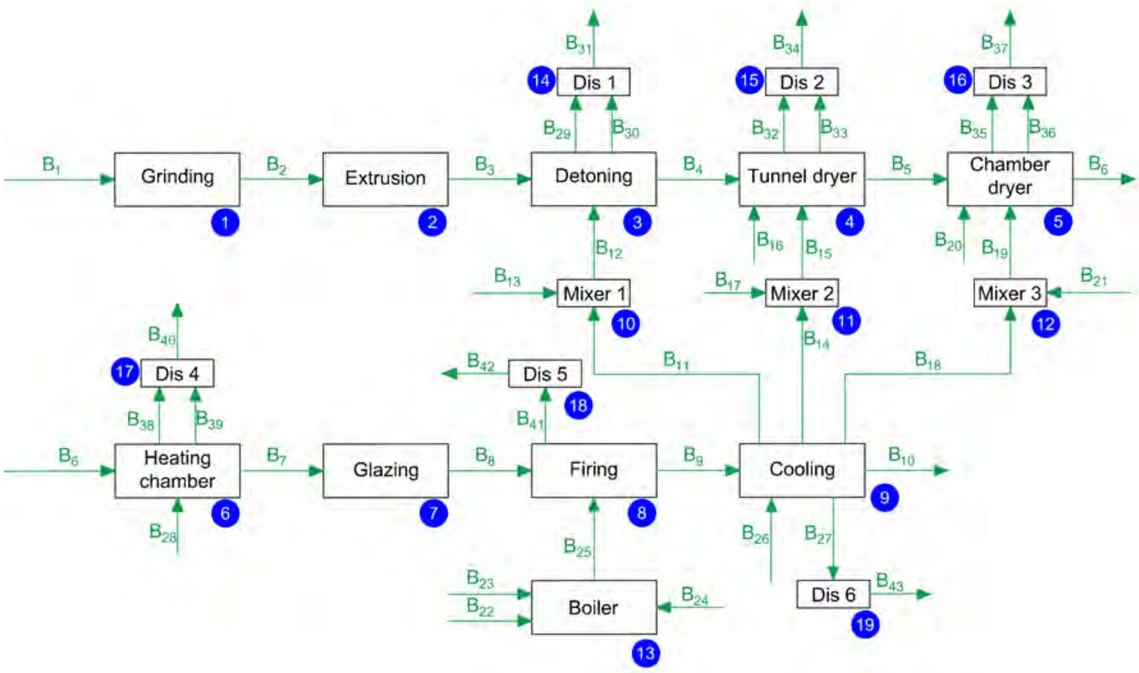

Figure 3. Process flow diagram of the studied ceramic production plant.

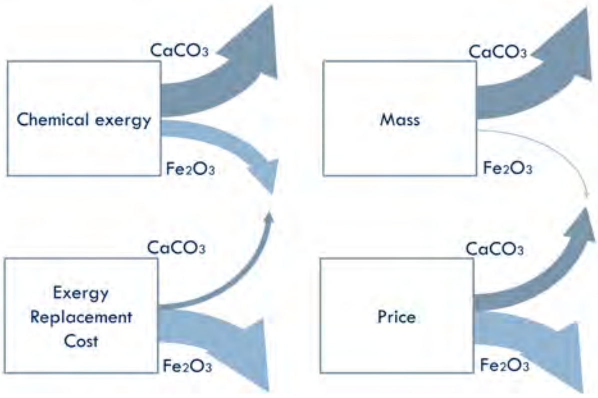

Figure 4. Cost allocation comparison.

2.2 Exergy analysis

Exergy is a thermodynamic property which measure the maximum potential work of a system, stream of matter or energy in relation to the reference environment. Furthermore, exergy could be defined as the minimum work required to produce goods from the reference environment. Four types of exergy have been considered to study the industries: chemical exergy, flow exergy, exergy replacement cost and electricity consumption.

2.2.1 Chemical exergy

Chemical exergy expresses the exergy of a substance at ambient temperature and pressure. It is defined as the maximum work which can be obtained when the considered substance is brought in a reversible way to the state of reference substances present in the environment, using the environment as source of heat and of reference substances necessary for the realization of the described process [8].

Standard chemical exergy results from a conventional assumption of a standard ambient temperature and pressure and standard concentration of reference substance in the natural environment. In case of this paper, chemical exergy of substances and mixtures have been calculated and obtained from different bibliography [8, 9].

Furthermore, fossil fuels are a type of minerals and therefore, their chemical exergies can be calculated by means of the methodology presented in [8]. However, the heterogeneity and complexity of the chemistry of fuels make the chemical exergy to be very difficult to predict through this method.

Additionally, it has been largely demonstrated that the chemical exergy of fossil fuels can be satisfactorily approximated to the HHV in many cases [10, 11].

2.2.2 Flow exergy

The specific exergy change can be evaluated using the following well-known equation:

$$b_1 - b_2 = (h_1 - h_2) - T_0(s_1 - s_2) + \frac{C_1^2 - c_2^2}{2} + g(z_1 - z_2) \tag{1}$$

2.2.3 Exergy replacement cost

When a mineral resource is used to produce a commodity or in a process, its life cycle is evaluated from the cradle (usually quarries) to the grave (disperse state). However, there is a cost that is not taken into account, it means from grave to cradle cost or, in terms of exergy, its Exergy Replacement Cost (ERC) [6, 12].

The exergy needed to concentrate a mineral resource from the grave (disperse state of mineral resources) to the cradle (natural disposals of minerals) is a bonus that the earth gives us for free. However, it is not taken into account in the conventional exergy analysis of non-energy flows. This type of flows are usually assessed by means of chemical exergy. If ERC are applied to the analysis, non-energy flows will be assessed in a fairer way. Additionally, cost allocation will be better distributed. We can seen in Fig. 4 a comparison between the cost allocation of limestone ($CaCO_3$) and limonite (Fe_2O_3), which are two important raw materials in the cement production process.

As we can seen, if the cost of limestone and limonite is allocated by means of chemical exergy and mass, limestone accounts a higher cost than limonite. However, limonite is a more scarcer and precious material than limestone. If their cost is distributed through ERC, the allocation is fairer and it is aligned with the price allocation. However, ERC is more stable than the price of mineral resources, because the last one depends on other external factors.

Therefore, the exergy of a mineral resource must have at least two components. The first one is associated to the chemical composition of the mineral resource, it means, its chemical exergy. The other one is related to its concentration. The concentration exergy represents the minimum amount of energy associated with the concentration of a substance from an ideal mixture of two components as below [13]:

$$b_{c,i} = -RT^0 \left[\ln x_i + \frac{(1-x_i)}{x_i} \ln(1-x_i) \right] \tag{2}$$

The exergy replacement cost is defined as the total exergy required to concentrate the mineral resource from the reference, with the best available technologies. From a theoretical point of view, the exergy cost of concentrating a mineral would require k times the minimum concentration exergy [6].

$$b^*_{ci} = k \cdot b_{ci} \tag{3}$$

Where k is a constant called unit exergy cost and it is the ratio between the real cumulative energy required to accomplish the real process to concentrate the mineral from the ore grade x_m to the commercial grade x, and the minimum thermodynamic exergy required to accomplish the same process [6].

$$k = \frac{E_{(x_m \to x_r)}}{\Delta b_{(x_m \to x_r)}} \tag{4}$$

2.2.4 Electricity

Electrical exergy is used to define the electrical consumption of processes or components. It coincides with the electrical energy consumption.

Engineering Equation Solver (EES) has been used in order to carry out the exergy analysis of the industries.

2.3 Thermoeconomic analysis

Thermoeconomics researches the connection between thermodynamics (second law) and economy (cost concept). By means of exergy, thermoeconomics provides a methodology which can evaluate, in terms of quantity and quality, energy and material losses, and its cost in terms of resources. This methodology is suitable for systems with large energy and material consumptions [14].

A productive structure is composed of n components, taking into account the environment which is considered as 0 component. The flows of exergy which are part of the product of the component i and the fuel of the component j are represented as B_{ij}. P_i and F_i are the product and the fuel of component i. So, fuel and product of each component could be defined as below:

$$\begin{aligned} P_i &= \sum_{j=0}^{n} B_{ij} \\ F_i &= \sum_{j=0}^{n} B_{ji} \end{aligned} \tag{5}$$

0 is included in the above equations in order to take into account the interaction with the environment. The table which contains all values of B_{ij} and the sum of rows and columns is denominated as fuel-product table.

On the other hand, the unit exergy consumption is defined as the exergy which each component requires from other components in order to obtain an unit of product:

$$\kappa_{ij} = \frac{B_{ij}}{P_j} \tag{6}$$

$\langle KP \rangle$ matrix is a matrix whose elements are the unit exergy consumptions, κ_{ij}. The unit exergy consumptions which are related to the environment (κ_{0j}) are shown in κ_e array. The unit exergy costs of the component product are shown in k^*_p.

Products of the system could be calculated from P_s, which is an array that shows the contribution of each component to the final product, as below:

$$P = (U - \langle KP \rangle)^{-1} P_s \tag{7}$$

The second equation provides the unit exergy cost of the products of all components:

$$k_p^* = (U - \langle KP \rangle^T)^{-1} k_e \tag{8}$$

The last equation provides information about the efficiency of each process of the system. Therefore, processes or components which present a low efficiency could be identified in order to improve the efficiency of the system.

Thermoeconomics provides a methodology in order to compare different scenarios too. It is known as thermoeconomic diagnosis and it is useful for verifying changes in the process such as different operation parameters or efficiency improvements.

The irreversibility variation on each process is due to two reasons:

- Malfunction (MF): The local irreversibility due to te variation of the efficiency of the process.
- Dysfunction (DF): The production variation due to the irreversibilities of other process

And it could be expressed as:

$$\Delta I_j = P_j \Delta k_j + (k_j - 1) \Delta P_j \tag{9}$$

Where the first term of the above equation is the malfunction, while the second term is the dysfunction.

On te other hand, the additional fuel consumption can be expressed as the difference between resources consumption of the plant in two scenarios, and it can be obtained through the sum of the irreversibilities of each component [15]:

$$\Delta F_T = \Delta I_T = \sum_{j=1}^{n} (I_j - I_j^0) = \sum_{j=1}^{n} \Delta I_j \tag{10}$$

Thermoeconomic Analysis of Energy Systems Software (TAESS) will be used in order to carry out the thermoeconomic analysis easily. It is a free software developed by CIRCE that can be found in the Exergoecology Portal [9].

3 Results and discussion

Exergy analyses require the operation parameters from the industries. These data were obtained from the factories and with them, the exergy analysis could be carried out. ERC have been calculated by means of specialized bibliography consulted [6, 12].

The results of exergy analysis are inputs for TAESS. The other input is the fuel-product definition of each process. By means of the correct definition of fuel-product and exergy flows, TAESS solves the thermoeconomic analysis. The usual production parameters has been considered as base case and several new scenarios have been proposed in order to assess their material and energy savings in terms of exergy. As it is shown in this paper, it is possible to assess the material efficiency of this industries through ERC methodology applied to thermoeconomics.

3.1 Cement plant case

The thermoeconomic analysis of the cement plant have been solved and their results are shown in Tab. 1. Processes that account the greatest unit exergy cost (k) are the less efficient. It have been proposed four new scenarios in order to assess the exergy savings that can be achieved. The new scenarios are described below:

- Scenario 1. Use of horizontal roller mills (Horomill) instead of ball mills: Horomill is a horizontal roller mill that involves a reduction in specific energy consumption (kWh/t) of 40-50 % regarding ball mills [16].

Process	Fuel [kW]	Product [kW]	I [kW]	k
Limestone crushing	41,124.3	3,892	37,232.3	10.6
Limestone conveyor belt	3,892	3,892	0	1
Limestone feed bin	3,892	3,892	0	1
Mill conveyor belt	3,892	3,892	0	1
Sand feed bin	562.6	59.7	502.9	9.4
Mill conveyor	59.7	59.7	0	1
Limonite feed bin	27.8	27.8	0	1
Mill conveyor belt	27.8	27.8	0	1
CaF_2 **feed bin**	12,634	51	12,583	247.6
Mill conveyor belt	51	51	0	1
Gypsum feed bin	7,319	92.5	7,226.5	79.2
Mill conveyor belt	92.5	92.5	0	1
Raw mill	7,143.2	4,649.5	2,493.7	1.5
Cyclone conveyor belt	4,220.4	4,209	11.4	1.003
Cyclone preheater	26,584	15,803.2	10,780.8	1.9
Rotary kiln	57,629	55,841	1,788	1.03
Enfriado	33,588.3	21,165	12,423.3	1.6
Mill conveyor belt	13,315.1	13,233	82.1	1.006
Cement mill	21,645.3	13,946	7,699.3	1.6
Packing machine	13,980.9	13,946	34.9	1.003
Petcoke mill burner	366.2	224.4	141.8	1.6
Petroleum coke mill	25,206.9	25,036	170.9	1.007
Fuel burner	67,504.2	43,635	23,869.2	1.6
Conditioning tower	3,467.5	2,025	1,442.5	1.7
Filter	2,025	1,157	868	1.8
Exhaust stack	1,157	1,083	74	1.07

Table 1. Results of thermoeconomic analysis of the cement plant. Reference scenario.

- Scenario 2. Greater amount of recycled materials from waste: When a natural resource is used, the earth give us a natural bonus for free. That is the exergy which is necessary to concentrate a natural resource from the disperse state to the concentration that the resource is found in the natural disposals. It means their Exergy Replacement Cost. This bonus is not considered by the conventional exergy analysis. As by-products do not come from natural resources, their ERC is 0.
  The application of the ERC allows to difference raw materials from waste and from natural resources. Otherwise, it is not possible with a traditional thermoeconomic analysis.

- Scenario 3. Thermal isolation of the cyclone preheater: There are thermal losses through the cyclone preheater of the plant. An isolation of the cyclones has been proposed in order to avoid these thermal losses.

- Scenario 4. Use of a larger amount of alternative fuels: The use of alternative fuels in the cement industry is an interesting way to reduce the high fossil fuel consumption of the manufacturing process of cement. It is supposed that 55 % of the fuel used is SRF, 35 % is biomass and 10 % is petroleum coke.

This scenarios proposed show exergy savings, as we can seen in Tab. 2. All scenarios give a value of resources savings, but it is necessary to take into account the provenance of this savings.

Scenario	Fuel Impact [kW]
Ball mill replacement	-1,961
Increase of raw materials from waste	-28,420.3 (Material savings in exergy units)
Cyclone isolation	-13,338.5
Increase of fuels from waste	-1,068.8

Table 2. Analysis of the different scenarios proposed to the cement case.

3.2 Fertilizer factory case

The analysis that have been carried out to a fertilizer production process shows that the greatest inefficiencies are the processes related to the input of raw materials, the drying process and the milling process. This analysis is shown on Tab. 3. It have been proposed three scenarios in order to decrease this inefficiencies:

- Scenario 1. Drying process optimization: The process of drying has a high unit exergy cost. It is supposed an optimization of this process in order to decrease the fuel consumption of the boiler and the drying gases that flow into the dryer. The drying optimization entails a 10 % reduction of the fuel consumption and the mass flow of gases.

- Scenario 2. Increase of raw materials from waste: The process studied does not use wastes as raw materials. Therefore, it is proposed an increase of the wastes in the raw material mix. It entails a reduction of the ERC as in the cement case. This scenario shows an exergy saving related to raw materials.

- Scenario 3. Increase of the mill efficiency: The milling process has a high electricity consumption. Therefore, it is proposed the use of a more efficient mill. The new mill entails a 20 percent reduction of the electricity consumption of this device.

It has been calculated the exergy savings of the described scenarios. The results of the diagnosis is shown in Tab. 4.

3.3 Ceramic production plant case

The ceramic factory studied produces several products. This analysis has been carry out to one product, assuming that it is produced in a continuously way. The results of the thermoeconomic analysis are shown in Tab. 5. In case of the ceramic industry studied, three new scenarios have been proposed and their exergy savings have been studied:

- Scenario 1. Thermal isolation of the kiln: The firing stage of the ceramic process shows a high unit exergy cost. It has been proposed an isolation of the kiln to increase their efficiency. The isolation entails a reduction of 7 % of the natural gas consumption.

Process	Fuel [kW]	Product [kW]	I [kW]	k
Conveyor belt 1	983.6	886.8	96.8	1.1
Conveyor belt 2	3,410	541.7	2,868	6.3
Conveyor belt 3	268.3	265.3	3	1.01
Mixer	1,754	1,675	79.2	1.05
Conveyor belt 4	1,369	1,360	8.8	1.006
Dryer	263.8	184.1	79.7	1.4
Boiler	1,597	394.7	1,203	4.05
Conveyor belt 5	1,345	1,342	3	1.002
Cooler	1,358	1,358	37.8	1.03
Conveyor belt 6	1,475	1,472	2.5	1.002
Sieve	1,472	1,472	0	1
Conveyor belt 7	1,137	1,137	0	1
Conveyor belt 8	154.1	151.6	2.5	1.02
Mill	264.1	151.6	112.5	1.7
Conveyor belt 9	156.1	151.6	4.5	1.03
Propeller	189.7	183.7	6	1.03
Dis 1	314.7	314.7	0	1
Dis 2	181	181	0	1
Dis 3	202	202	0	1

Table 3. Results of thermoeconomic analysis of the fertilizer factory. Reference scenario.

Scenario	Fuel Impact [kW]
Drying process optimization	-141.2
Increase of raw materials from waste	-2,956 (Material savings in exergy units)
Increase of the mill efficiency	-22.5

Table 4. Analysis of the different scenarios proposed to the fertilizer case.

Process	Fuel [kW]	Product [kW]	I [kW]	k
Grinding	604.8	15.6	589.2	38.8
Extrusion	15.6	15.6	0	1
Detoning	0.2	0.1	0.2	3.5
Tunnel dryer	4.2	1.1	3.1	3.8
Chamber dryer	186.9	145.5	41.4	1.3
Heating chamber	32.4	8	24.4	4.1
Glazing	15.5	4	11.5	3.9
Firing	6,984.1	943.3	6,040.8	7.4
Cooling	942.8	558.5	384.3	1.7
Mixer 1	3.3	1.7	1.6	1.9
Mixer 2	35.1	16.8	18.3	2.1
Mixer 3	298.4	277.6	20.8	1.1
Boiler	8,050	7,374.1	675.9	1.1
Dis 1	1.6	1.5	0.1	1.1
Dis 2	14.1	13.1	1	1.1
Dis 3	306.5	244.7	61.8	1.3
Dis 4	35.5	34	1.5	1
Dis 5	410.9	410.9	0	1
Dis 6	288.4	288.4	0	1

Table 5. Results of thermoeconomic analysis of the ceramic plant. Reference scenario.

- Scenario 2. Greater amount of raw materials from waste: As well as the cement and the fertilizer cases, it has been proposed a scenario where the amount of raw materials from natural resources decreases. The new raw materials come from waste.
- Scenario 3. Reduction of the humidity of the ceramic paste: A reduction of the paste humidity is simulated in this case. It entails a reduction of the thermal demand to dry the paste.

Exergy savings related to the new scenarios are shown in Tab. 6. The material savings in this case are lower than the cement and fertilizer case due to the quantity of raw materials introduced to the process is lower.

Scenario	Fuel Impact [kW]
Kiln isolation	-1,281.3
Increase of raw materials from waste	-294.6 (Material savings in exergy units)
Decrease of paste humidity	-57.5

Table 6. Analysis of the different scenarios proposed to the ceramic case.

4 Conclusions

The following conclusions can be drawn from the application of Exergy Replacement Cost to the thermoeconomic analysis of resource-intensive industries.

- Thermoeconomics has been proofed to be helpful in the efficiency assessment of resource-intensive industries. Thermoeconomics uses exergy in order to characterize the flows of a system. Exergy property allows the integration of material and energy flows, since exergy is a physical property that measures the quality of a system in the same units (kW).
- Exergy Replacement Cost is a valid indicator to measure the material efficiency in industries. By means of the application of ERC, the benefits of using by-products from other industries can be evaluated. Therefore, the use of raw materials of industries and their source can be assessed. Otherwise, there are not any exergy difference between raw materials from waste and from natural resources.
- Thermoeconomics, along with ERC in order to assess non-energy resources, provides the possibility to evaluate industrial symbiosis systems and improve the resource efficiency of single industries. Material savings of industrial symbiosis systems can be assessed more accurately by means of ERC.
- It is necessary to find an optimum between energy and material efficiency. In terms of exergy savings, the total replacement of raw materials from quarries is the best option. However, resources from waste are limited and the energy required to produce them increases with their demand due to the cost of transportation and manufacture. For this reason, it is necessary to analyze the possibilities of waste use in order to optimize energy and material savings. Therefore, material savings is not a target, it is an indicator of the material efficiency of the industry in terms of exergy.
- It would be interesting to develop a methodology that assesses resource-intensive industries by means of thermoeconomics in order to define weak points and improvements of these systems. This tool would be helpful in case of industrial symbiosis systems due to the large quantity of interaction possibilities between industries.

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References

[1] Yehia M. El-Sayed and R. B. Evans. Thermoeconomics and the design of heat systems. *Journal of Engineering for Power*, January:27–35, 1970.

[2] George Tsatsaronis. Thermoeconomic analysis and optimization of energy systems, jan 1993.

[3] A. Valero, M. A. Lozano, L. Serra, and C. Torres. Application of the exergetic cost theory to the CGAM problem. *Energy*, 19(3):365–381, mar 1994.

[4] Sergio Usón and Antonio Valero. Thermoeconomic diagnosis for improving the operation of energy intensive systems: Comparison of methods. *Applied Energy*, 88(3):699–711, 2011.

[5] Adriana Dominguez, Alicia Valero, and Antonio Valero. Exergy accounting applied to metallurgical systems: The case of nickel processing. *Energy*, 62:37–45, 2013.

[6] Alicia Valero, Antonio Valero, and Adriana Domínguez. Exergy replacement cost of mineral resources. *Journal of environmental accounting and management*, 1(1):147–148, 2013.

[7] Antonio Valero, Sergio Usón, César Torres, Alicia Valero, Andrés Agudelo, and Jorge Costa. Thermoeconomic tools for the analysis of eco-industrial parks. *Energy*, 62:62–72, dec 2013.

[8] Jan Szargut. Chemical exergies of the elements. *Applied Energy*, 32(4):269–286, 1989.

[9] Centro de Investigación de Recursos y Consumos Energéticos (CIRCE). The Exergoecology Portal, www.exergoecology.com, 2016.

[10] Z. Rant. Zur Bestimmung der spezifischen Exergie von Brennstoffen. *Allgem. Waermetechn.*, 10:172–176, 1961.

[11] Jan Szargut and T. Styrylska. Approximate evaluation of the exergy of fuels. *Brennst. Waerme Kraft*, 16:589–596, 1964.

[12] Antonio Valero and Alicia Valero. *Thanatia: the destiny of the earth's mineral resources*, volume 1. World Scientific, 2014.

[13] Malte Faber, Horst Niemes, and Gunter Stephan. *Entropy, Environment and Resources*. Springer-Verlag, Berlin, Heidelberg, New York, 1987.

[14] Antonio Valero, César Torres, and Luis Serra. A general theory of thermoeconomics: Part I. Structural analysis. In *Proceedings of the International Symposium on Efficiency, Costs, Optimization and Simulation of Energy Systems*, pages 137–154, 1992.

[15] César Torres, Antonio Valero, Luis Serra, and Javier Royo. Structural theory and thermoeconomic diagnosis. *Energy Conversion and Management*, 43(9-12):1503–1518, jun 2002.

[16] Namik A. Aydogan and Hakan Benzer. Comparison of the overall circuit performance in the cement industry: High compression milling vs. ball milling technology. *Minerals Engineering*, 24(3-4):211–215, feb 2011.