# Energetic and exergetic efficiencies in the cement industry

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**Abstract**

The cement industry is one of the largest energy consumers in the world so energy efficiency in this sector is very relevant for the development a sustainable future. In Portugal it is the second largest industry in terms of energy consumption, therefore a cement producing plant in Alhandra was chosen to be studied in this dissertation.

In this thesis, exergy efficiency was chosen to evaluate energy efficiency. Exergy is a property that takes into account the quality of the energy, in other words, exergy is the maximum amount of work an energy flow could do.

In this dissertation two different types of exergy efficiencies were calculated: aggregated efficiencies, calculated at the plant level, and disaggregated efficiencies, calculated at the process level. In order to calculate the efficiencies at the process level, it was assumed that the Alhandra plant was similar to another one described in the literature, to fill in for missing data, crucial for this work. Aggregated efficiencies were calculated using publicly available information from the environmental declaration of the Alhandra plant and using information about the chemical composition of the various products during the different stages of production, from Cimpor. In addition to these two kinds of exergy efficiencies, it was also calculated the change of energy intensity in the Alhandra plant.

The efficiencies obtained for each process were similar to other studies. Aggregated efficiencies were constant in the years used in this study, the exergy efficiency calculated using useful exergy was close to 48% for all the years of this study, while the primary exergy efficiency was around 20%. Concerning the thermal energy intensity, it was consistent with what was expected for this type of plant, with an average of 3.44 GJ/t clinker for the studied period. Regarding electrical energy consumption, it was significantly larger than the values of other studies, with an average for the studied period of 114 kWh/t. For $CO_2$ emissions, the results show that there is a trend of increasing emissions per tonne of clinker.

**Keywords:** Exergy**;** Exergy efficiency; Energy intensity; Cement industry;

## 1. Introduction

Usually energy consumption is divided in three sectors, buildings, industry and transports. The energy consumption of industry accounts for 30% of the total energy consumption (IEA, 2007).

The cement industry represents around 7% of the world energy consumption using mainly coal and pet coke as energy carriers. Consequently, it emits about 7% of anthropogenic global $CO_2$ emissions (IEA and CSI, 2018). In the cement industry, half of the carbon dioxide emissions are process emissions (calcination), while the other half comes from the fuels burned (Hendriks et al., 2004).

Energy can be studied is three different stages: primary energy, where the energy has not undergone any transformation (coal or petroleum for example); final energy, the energy that is delivered to the consumers (for example electricity and diesel) and useful energy, the energy that really does the function wanted (for example heat and lighting).

In this dissertation, energy will be measured as exergy, which is a way of quantifying the quality of energy. In other words, it is the maximum amount of work a certain amount of energy may originate (Serrenho et al., 2016).

The exergy analyses may be used to evaluate if a process is near the ideal process.

Usually exergy efficiency in the cement industry is evaluated for each process individually.

In this work, exergy efficiency will be analysed process by process, in order to compare it to the literature, although it will also be calculated the aggregated efficiency of the Alhandra Production Center (APC).

### 1.1. Cement manufacturing process

The cement manufacturing process includes three main stages: preparation of raw materials, clinker production and clinker grinding with other products in order to produce cement.

There are two basic types of clinker production, wet or dry. Nowadays the dry process is the most common and it is used in Alhandra.

In the dry production, after being quarried, the raw materials are mixed in a process called prehomogenisation. Then they are milled to produce a fine powder called raw meal.

The next stage is the production of clinker. This occurs in three main equipment. The first one is the pre-heater tower which is, composed of cyclones, were the raw meal is heated by the kiln exhaust gases that are moving in the opposite direction. Next the raw meal is calcinated, the limestone is decomposed in to lime releasing carbon dioxide, in a equipment called precalciner. The last device is the rotary kiln where the raw meal reaches temperatures of up to 1450 ºC. The heat causes chemical reactions that melt the meal forming clinker.

After this the clinker is cooled rapidly in the cooler, using air currents.

Afterwards the clinker is blended with other materials, mainly gypsum. This mixture is ground in to a grey powder known as cement.

## 2. Methods

In this work were used two different methodologies. One for the evaluation of the disaggregated efficiency (meaning the efficiency of each process) and other for the aggregated efficiency (at the plant level).

Due to lack of data of the studied plant, a similar plant found on the literature was used to calculate the exergy efficiency for each process. This case study was analysed in Fellaou and Bounahmidi (2017, 2018).

For the aggregated efficiency, publicly available information was used.

### 2.1. Exergy efficiency at process level

In order to calculate the exergy efficiency of each process it was assumed that the Alhandra plant was similar to the case studied in Fellaou and Bounahmidi (2017, 2018). This assumption was at least partially valid because both plants used a similar production process with similar number of cyclones in the pre-heater tower. As well as both having also a pre-calciner and a grate cooler.

The case study only presents values for energy, so the exergy was calculated using the following equations(Moran et al., 2013):

$$h(T_i) - h(T_0) = c_p(T_i - T_0) \qquad (1)$$

$$h(T_e) - h(T_0) = c_p(T_e - T_0) \qquad (2)$$

$$s(T_i) - s(T_0) = c_p \ln\frac{T_i}{T_0} - R\ln\frac{p_i}{p_0} \qquad (3)$$

$$s(T_e) - s(T_0) = c_p \ln\frac{T_e}{T_0} - R\ln\frac{p_e}{p_0} \qquad (4)$$

$$s_i - s_0 = c \ln \frac{T_i}{T_0} \quad (5)$$

$$s_e - s_0 = c \ln \frac{T_e}{T_0} \quad (6)$$

In the previous equations (1, 2, 3, 4, 5 e 6) the subscripts i and e means entrance of the process and exit of the process, respectively. The subscript 0 represent the environment conditions. The variable T represents temperature, h represents specific enthalpy, s specific entropy, cp specific heat at constant pressure, c specific heat, p represents the pressure and R the ideal gas constant. Equations 3 and 4 were used for gases and it was assumed they behave like ideal gases. While equations 5 and 6 are used for the other substances, it was assumed they were incompressible substances. Since the differences of pressure are negligible, the right term of equation3 and 4 can be discarded. Afterwards the following equation was used to calculate the specific exergy flow.

$$b_f = h - h_0 - T_0(s - s_0) \quad (7)$$

In equation 7 $b_f$ is the specific exergy flow, the kinetic and potential energies were neglected.

The specific exergy flows of each substance was then multiplied by the mass flow in order to obtain the exergy flow. With this the physical exergy was calculated.

The chemical exergy for the raw materials and the cement was calculated using Morris and Szargut (1986). The chemical exergy of gases was neglected.

Energy balances and exergy balances were computed for each process in order to verify the calculations.

### 2.2. Aggregated efficiencies

The aggregated efficiencies are calculated at the plant level meaning that it is only necessary to know what enters and what exits of the plant. This data, such as cement, fuel, electricity and raw materials consumption, was obtained from the environmental declarations. The composition of the raw materials and cement, necessary to calculate the chemical exergy, were provided by a contact inside the Alhandra plant.

Fuel data was in mass units used for each of the fuels used in Alhandra. So, it was necessary to transform it in energy and then exergy. To transform to energy the low heating value was used and then to calculate the exergy the energy was multiplied by the factors presented in table 1.

Table 1 - Exergy factor for each energy carrier (Ertesvåg and Mielnik, 2000)

| Energy carrier | Exergy factors |
|---|---|
| Electricity | 1 |
| Oil and Petroleum products | 1.06 |
| Natural gas | 1.04 |
| Coal | 1.06 |
| Coke | 1.05 |
| Biomass | 1.11 |

Afterwards the primary and useful exergy were calculated. In order to calculate the primary exergy, the final exergy was multiplied by the factors presented in table 2.

Table 2 - Factors used to transform final exergy in primary exergy (DGEG, 2008; Elgowainy et al., 2014)

| Energy carrier | Factor final/primary |
|---|---|
| Electricity | 2.50 |
| Pet coke | 1.08 |
| Alternative fuels | 1.00 |
| Biomass | 1.00 |
| Fuel oil | 1.06 |
| Diesel | 1.10 |
| Propane gas | 1.00 |

To calculate the useful exergy, it was applied the following equation:

$$\varepsilon = \frac{\dot{B}_g + Exergy_{reaction}}{\dot{m} * LHV * f} \quad (8)$$

In equation 8 $\dot{B}_g$ is the exergy of the useful exhaust gases of the kiln, $\dot{m}$ is the mass flow, LHV is the low heating value and f the exergy factor. This exergy efficiency was calculated using data from the Morocco case study (Fellaou and

Bounahmidi, 2017, 2018). The value obtained was 45%, so the final exergy of the fuels was multiplied by 0.45. For the electricity it was assumed that the useful exergy was equal to the final exergy.

## 3. Results

### 3.1. Results for the process level analyses

In this section the results for the process level analyses are presented. These results are based in the data available for the Morocco case study (Fellaou and Bounahmidi, 2017, 2018).

For this case study were calculated three different exergy efficiencies. Two considering chemical exergy and one without chemical exergy. The following equations were used to calculate the different exergy efficiencies.

$$\varepsilon = \frac{Exergy_{out}}{Exergy_{in}} \quad (9)$$

$$\varepsilon = \frac{Exergy_{out} - Exergy_{wasted}}{Exergy_{in}} \quad (10)$$

*Table 3* – Exergy efficiencies calculated for each process

| | $\varepsilon_{T\ Eq.9}$ (%) | $\varepsilon_{T\ Eq.10}$ (%) | $\varepsilon_{F\ Eq\ 9}$ (%) |
|---|---|---|---|
| Raw mill 1 | 33.73 | 13.42 | 24.91 |
| Raw mill 2 | 33.07 | 14.67 | 23.33 |
| PPKC* | 53.46 | 42.75 | - |
| Pet coke mill | 98.42 | 98.29 | 8.61 |
| Cement mill | 92.50 | 91.73 | 11.12 |

*System composed by the preheater, precalciner, kiln and cooler.

There are three different exergy efficiencies shown in table 3, the first one ($\varepsilon_{T\ Eq.9}$) was calculated with equation 9 and considering chemical exergy. The second one ($\varepsilon_{T\ Eq.10}$) was calculated with equation 10 and considering chemical exergy. The last one ($\varepsilon_{F\ Eq\ 9}$) was calculated with equation 9 but only considering the physical exergy (neglecting chemical exergy), this equation was used in most cases to compare to the literature.

The values obtained for the raw mills using only physical exergy and equation 9 were similar to other studies. Utlu et al. (2006) obtained an exergy efficiency of the raw mill of 25.2%, close to the one calculated using only physical exergy. In Atmaca and Kanoglu (2012) the value obtained was lower, 16.4%.

For the system PPKC the values were only obtained considering chemical exergy and similar to the literature. Sogut et al. (2010) calculated the exergy efficiency, of the system PPKC as 49% similar to the value obtained using equation 9.

The next process evaluated was the pet coke mill and in this case the results were different from the literature. In Sogut and Oktay (2008) study the exergy efficiency of the pet coke mill was calculated to be 18%, more than double the value obtained for the Morocco study (8,61%). However in the Sogut and Oktay study the electricity was negleted which was probably the cause for the disparity in the efficiencies.

Finally, the cement mill value obtained using only physical exergy was similar to the literature values. According to Atmaca and Yumrutaş (2014) the exergy efficiency of this mill was 9.5% similar to the value obtained 11.1%.

### 3.2. Results for the APC

In this section the results obtained for the APC are shown for the period between 2008 and 2016.

#### 3.2.1. Energy use in APC

In Figure 1 is shown the final energy shares per energy carrier, in APC. In this figure can be observed that the share of biomass is declining during the studied period while the alternative fuels share increases. The electricity share is somewhat constant.

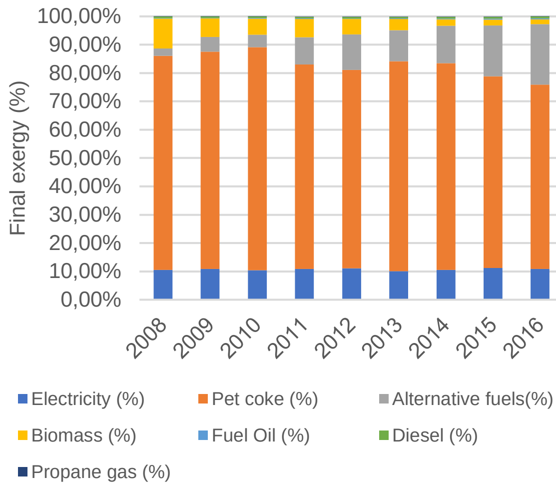


Figure 1 – Final exergy shares per energy carrier, from 2008 to 2016

### 3.2.2. Cement production in APC

In this section the cement production is analysed. Figure 2 shows the change in cement production in the studied period.

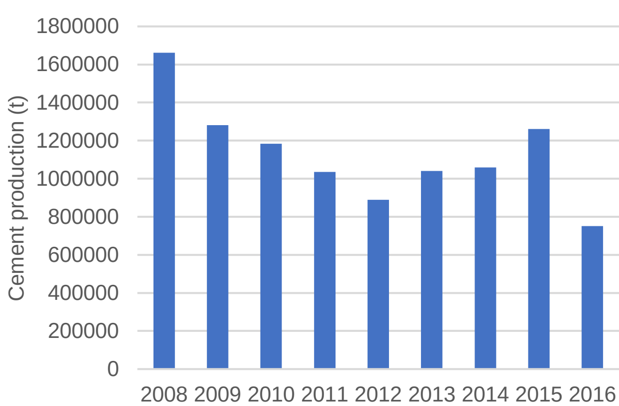


Figure 2 – Cement production in APC, from 2008 to 2016

The production of cement decreased in the period between 2008 and 2012 but increased from 2012 to 2015. In 2016 it reached lowest value of production in the studied period.

In the next figure the clinker production is shown.

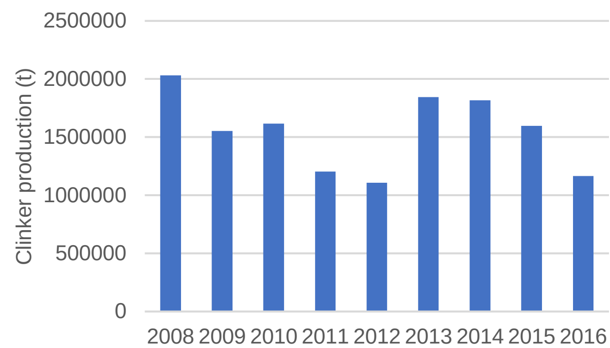


Figure 3 – Clinker production in APC, from 2008 to 2016

In Figure 3 represents the clinker production in APC. The production of clinker does not follow exactly the same trend as cement production because, as it will be shown in the next figure, not all of the clinker is used to make cement. So, for clinker the year with the lowest production was 2012.

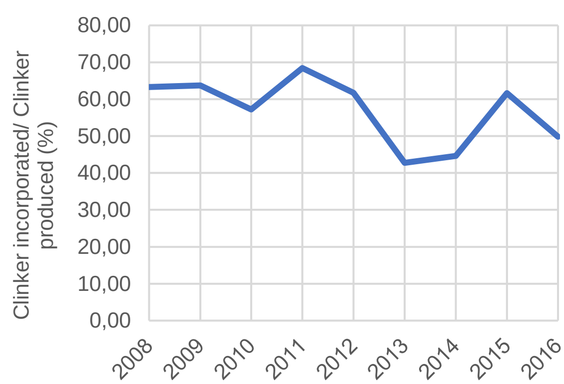


Figure 4 – Evolution of the percentage of clinker produced that was incorporated in cement

Figure 4 highlights that not all of the produced clinker is used to make cement meaning that some of the clinker is sold as a final product. This graph allows a better understanding of the mismatch between clinker production and cement production since some of the clinker is sold producing more clinker in one year does not mean that year will produce more cement. The opposite is also true a year with a smaller clinker production like 2015 can produce more cement than 2014 because a larger portion of clinker is actually used to produce cement.

### 3.2.3. Energy intensity of APC

In this section the energy intensity of APC is going to be shown and discussed. Since not all of the clinker produced in APC is incorporated in cement a value for the cement that will be produced if all clinker was incorporated was calculated in order to prevent an overestimation of the energy intensity. This value will be named cement equivalent (ceq).

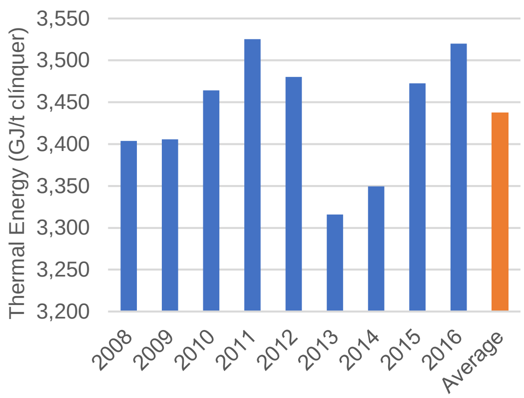


Figure 5 - Thermal energy consumed per tonne of clinker of the APC, from 2008 to 2016

Figure 5 presents the thermal energy consumption per tonne of clinker for each year of the studied period in blue, and in orange the average of the same period. The year with the smallest thermal intensity was 2013.

According to ECRA and CSI (2017) the global average (considering all technologies and 21 % of the world production) was in 2014 3.51GJ/ t clinker, which means that in the APC only 2011 and 2016 are above this value. The same report states also that the dry process with precalcining technology is state of the art. This technology can have a variable number of cyclones and as the number of cyclones increases the thermal energy consumption decreases. As stated in ECRA and CSI (2017) the energy intensity for a plant with 4 cyclones should be between 3.2 and 3.6 GJ/t clinker and for a plant with 5 cyclones it should be between 3.1 and 3.5GJ/t clinker. Since the APC has a line with 4 cyclones and another with 5 cyclones the average value for the period (3.44 GJ/t clinker) is inside the expected interval.

Nowadays the most efficient producer of cement is Japan using 3GJ/t clinker (IEA, 2007, 2009). The minimum value of thermal energy consumption that can be achieved using the best available technology is 2.9GJ/t clinker as reported by (Madlool et al., 2011).

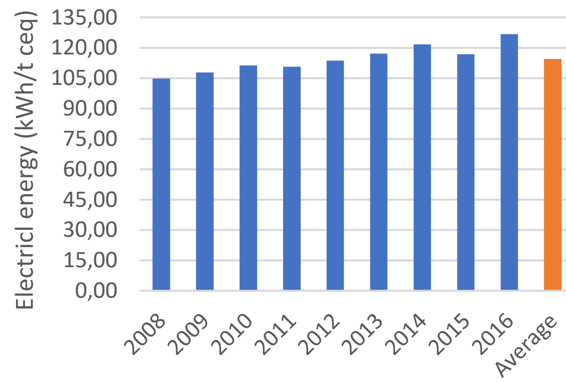


Figure 6 - Electrical energy consumed per tonne of cement equivalent, from 2008 to 2016

In Figure 6 is shown the evolution from 2008 to 2016 of the electrical energy consumed per tonne of cement equivalent in blue, and in orange the average for the same period. The year with the lowest consumption of electrical energy is 2008.

According to ECRA and CSI (2017), in 2014, the global average (considering all technologies and 21 % of the world production) of energy consumption per tonne of cement (in the APC equivalent cement is used to compare) was 104kWh/t. Considering that the average value for the APC is 114 kWh/t the conclusion is that the APC uses more electricity than the global average. Moreover, in all the years of the studied period the electrical energy consumption is higher than the global average, even in 2008 the consumption was 105 kWh/t ceq. In other words it is clear that there is room for improvement.

It is stated in ECRA and CSI (2017) that is foreseeable a decline to 100 kWh/t until 2030 and to 90 to 95 kWh/t in 2050. Hence there is only a small room for improvement if considered the global average.

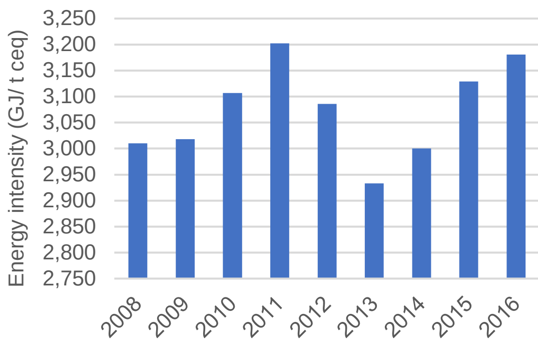


Figure 7 – Energy intensity considering final energy, from 2008 to 2016

In Figure 7 is indicated the final energy intensity for each year of the studied period. It is possible to see that 2013 was the least energy intensive year while 2011 was the most energy intensive.

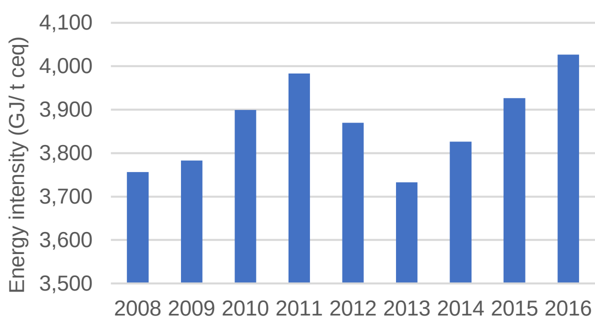


*Figure 8 – Energy intensity considering primary energy, from to 2008 to 2016*

In Figure 8 is shown the primary energy intensity for each year of the studied period. Is possible to state that 2013 was again the least energy intensive year while 2016 was the most energy intensive. The reason why 2016 was more energy intensive, considering primary energy, than 2011 (which was the most energy intensive in terms of final energy) is that in 2016 there is a larger consumption of electricity (see Figure 6).

#### 3.2.4. Aggregated exergy efficiencies

In this section the aggregated efficiencies for the APC will be analysed. In order to calculate the aggregated efficiencies, the following equation were used (Carmona et al.):

$$\varepsilon = \frac{Exergy_{\ out\ mat\ .}}{Exergy_{in\ mat.} + Exergy_{\ Usef.fuels}} \quad (11)$$

$$\varepsilon = \frac{Exergy_{\ out\ mat}}{Exergy_{\ in\ mat.} + Exergy_{\ Prim.fuels}} \quad (12)$$

In equation 11 and 12 exergy $_{\text{out mat.}}$ is the chemical exergy of the cement when it leaves the plant and exergy $_{\text{in mat.}}$ represents the chemical exergy of the raw material that enters the plant. In equation 11 exergy $_{\text{Usef. fuels}}$ means the useful exergy of the fuels and in equation 12 exergy $_{\text{Prim. fuels}}$ stands for the primary exergy of the fuels. The results obtained using these two equations are in the next figure.

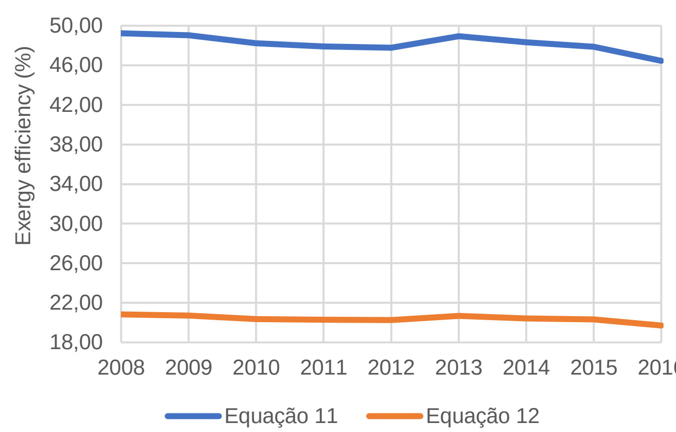


Figure 9 – Exergy efficiency calculated with equation 11 and equation 12

In *Figure 9*, the blue line represents the efficiency calculated using equation 11 (useful exergy) and the orange line represents the efficiency calculated with equation 12 (primary exergy). As it was expected the efficiency considering useful exergy is bigger than the one considering primary exergy. The average value for the useful exergy was 48% in the studied period, the year of 2008 was the most efficient year and 2016 the least efficient one. The average value for the primary exergy was 20%, the most efficient year was 2008 and least efficient one was 2016.

### 3.2.5. Carbon dioxide emissions

In this section the carbon dioxide emissions of APC are going to be presented and discussed.

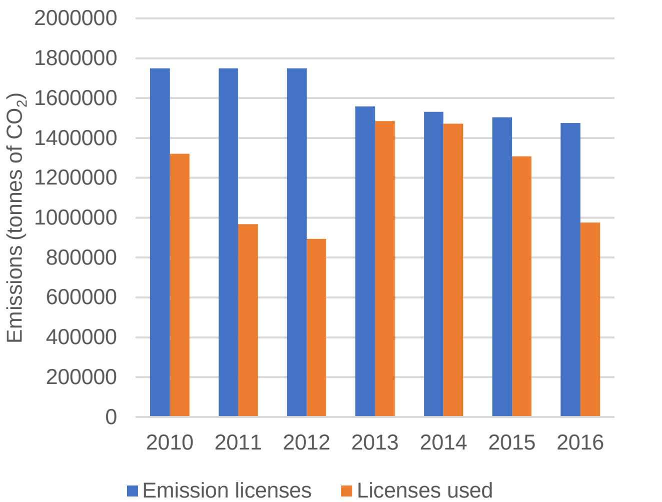


Figure 10 – Comparison between the emissions licenses and licenses used in APC, from 2010 to 2016

In Figure 10 are shown the emission licenses, in blue, and the licenses used, in orange. The emission licenses were attributed under the European Union Emissions Trading Scheme (EU ETS). As it shown in the graph APC always had enough licenses for the emissions made. It is also understood that the licenses used were highly correlated with the production of clinker (see figure 3).

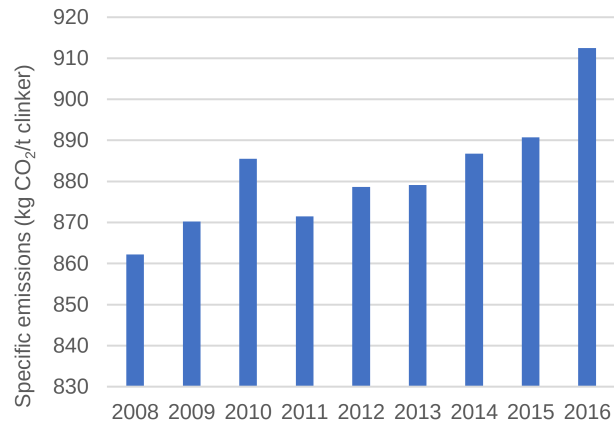


Figure 11 – Specific emissions of $CO_2$ per tonne of clinker, from 2008 to 2016

In Figure 11 are presented the specific emissions of $CO_2$ per tonne of clinker. In the studied period the specific emissions are increasing this can be explained by the decrease of a carbon neutral fuel, biomass (see figure 1).

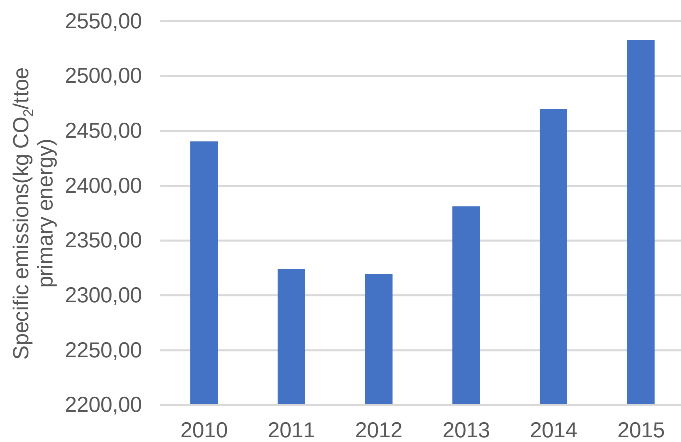


Figure 12 – Specific emission of $CO_2$ per tonne of oil equivalent of primary energy, from 2010 to 2015

In Figure 12 are shown the specific emission of $CO_2$ per tonne of oil equivalent of primary energy. These emissions have been increasing in the last years, since 2012. This increase might be due to a decrease in the use of biomass.

## 4. Conclusions

The rational use of energy is nowadays a necessity in every sector. Bearing in mind the importance of cement industry as a consumer of energy is very important that efficiency is studied in this industry.

The results obtained for the efficiencies at the process level are in line with the literature. The exergetic efficiencies calculated using only physical exergy were found to be: 24.91% for the raw mill 1, 23.33 % for the raw mill 2, 53.46% for the system PPKC, 8.61% for the pet coke mill and 11.61% for the cement mill.

Regarding energy intensity, the obtained results are in the expected range taking in to account the type of plant studied (APC). In average the energy consumed was 3.44 GJ/t clinker, in the studied period. The best available technology can decrease this consumption to 2.9 GJ/ t clinker.

Concerning electrical energy consumption, during the period studied, the average value was 114 kWh/t which is higher than what was expected since the global average is 104 kWh/t.

About the aggregated efficiencies they were more or less constant in the interval of years studied. The aggregated efficiency calculated using useful exergy was close to 48% during all the period of study, while the primary exergy efficiency was 20% in the same period.

In regard to $CO_2$ emissions there is clear trend for an increase of specific emissions. These increased in a product basis (the specific emissions increased from 862 kg $CO_2$/t clinker in 2008 to 912 kg $CO_2$/t clínquer in 2016) and in an energy basis (the specific emissions increased from 2440 kg $CO_2$/toe of primary energy in 2010 to 2533 kg $CO_2$/toe of primary energy in 2015).

In future studies it will be interesting to obtain real data from a cement plant, in order to then try to implement measures to increase its efficiency.

It will be also interesting if the methodology used for aggregated efficiency was replicated in other plants to see what values will be obtained in order to compare them and to establish benchmarks. Another interesting study is to develop a longer time series for a better understanding how the exergy efficiency changes throughout the time.

In the future other construction materials should be studied, or simply other production process for cement, in order to say if there is a better way (using less energy and less materials) of building our houses and infrastructure.

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