

## COGENERATION POTENTIAL ASSESSMENT IN CEMENT INDUSTRY

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**Abstract.** *The evaluation of the potential for cogeneration in the cement industry aimed to study the cement manufacturing process in order to identify the possible sources for the recovery of waste heat and electricity generation. Several power generation technologies were studied to carry out the potential the generation power and estimates its implementation cost. To achieve the power calculations that can be generated in a cement plant, we initially determined the potential energy available in the pre-cyclone and the clinker cooler. For simulation purpose, it was used a cement process data referenced in the literature provisions of the parameters required for the calculation as flow, temperature and specific heat of the combustion gas. In Microsoft Excel software, an interactive spreadsheet to estimate energy cogeneration using four models of thermodynamic cycles was created. From the completion of the input data, one can estimate the energy generated power for "single flash" and "dual-pressure steam" Rankine cycles, Kalina cycle and Organic Rankine cycle. From the literature researched, we adopted the thermal efficiencies used for the calculations. The "single flash" Rankine cycle which has 25.7% of thermal efficiency achieved better results, and 11,188.56 kW of energy. In contrast, the Organic Rankine cycle was the one that generated less energy, 8968.27 kW, with a thermal efficiency of 20.6%. Despite "single flash" and "dual-pressure steam" Rankine cycles, have reached higher values of cogeneration in kW, calculation results suggests the continuation of the study applying data and real variables in the production process of a cement industry to the energy cogeneration potential calculations. In this sense, the use of the Kalina cycle has the possibility of varying the concentration of working fluid in each stage of the cycle and of raising the thermal efficiency.*

**Keywords:** *Residual Heat, energy potential, thermal efficiency, thermodynamic cycle.*

### 1. INTRODUCTION

In the Brazilian industrial context, one of the most produced products is the cement, since it is the main raw material used in construction and, according to the National Brazilian Energetic Balance (MME/EPE 2014), industries are responsible for the increased consumption of electricity in the country. By linking this information with the decreasing availability of natural resources for energy production, we perceived the need to investigate possible heat reuse technologies for electricity generation. Furthermore, some steps of the manufacturing cement involve high temperature thermal energy and generate a residual heat that is lost to the environment. Thus, the application of heat recovery techniques may be critical to the reduction of energy consumption. To this end, the use of thermodynamic cycles to transform wasted thermal energy into mechanical work, which is supplied to an electric generator is required. Thus, this study aimed to evaluate the potential for cogeneration in the cement industry based on available energy data, due to the clinker production capacity. That is, we intend to study the manufacturing process in order to identify the possible sources for heat recovery technologies available for conducting such a process, its potential for cogeneration and the costs for system implementation.

### 2. LITERATURE REVIEW

The cogeneration plants can recover waste heat available in the exhaust preheater and the clinker cooler exhaust gases and generate electricity on a continuous basis without interfering with the core clinker production process. Observed that, Wang, Dai and Gao (2009) conducted this study with the objective of examining the exergy analysis for each cogeneration plant, a single expansion steam cycle, the double pressure steam cycle, organic Rankine cycle and the Kalina cycle. The exergy analysis is a powerful tool that has been successfully used in evaluating design and performance related to the energy systems. For each cogeneration system examined, a parameter optimization was made which was achieved by genetic algorithm (GA) to achieve maximum exergetic efficiency. In addition, optimal performance of different cogeneration plants was compared under the same conditions typical of a line capacity of 5000 tons of clinker per day (tc/day) oven. For the single expansion steam cycle and the dual-pressure steam cycle, it was noted that the largest loss of exergy due to irreversibility occurred in the turbine expansion and the condensation process proved to be the second largest loss of exergy. For organic Rankine cycle, higher exergy loss occurred due to the irreversibility in the process of condensation because the turbine exhaust temperature is relatively high and the second greatest loss occurred in the preheater of the boiler suspension. For the Kalina cycle, greater loss of exergy occurred in the absorption process and the second largest loss occurred in the process of heat addition. Since the amounts of exergy loss in the turbine, the condenser,

preheater and the clinker cooler showed a large percentage, it is significant to employ methods for reducing losses of exergy of these components. Thus, the performance for the cogeneration system can achieve a great improvement. Compared with other cogeneration systems in cement factory, the Kalina cycle can achieve the best performance from the standpoint of exergy efficiency, and organic Rankine cycle shows a lower exergetic efficiency under the same condition.

In another study related to the topic, Engin and Ari were aimed to do an energy audit of a rotary dry-type furnace system that works in a cement company located in Turkey, presenting and discussing some possible ways to recover heat losses from the plant (ENGIN; ARI, 2005). First it was performed a detailed thermodynamic analysis of the kiln system and then the possible heat recovery approaches based on the major sources of loss were discussed. For the audit, it was carried out a large number of measurements for two years and the average of these values was used in the study performed. From the data obtained, it was made mass and energy balance based on some considerations about the system, such as working conditions on a permanent basis, negligible change in ambient temperature, negligible cold air leak in the system, raw material compositions, between others. According to the results, it was shown that the system has an efficiency of 48.7%. It was seen that the major sources of heat loss in the plant were, in decreasing order, the kiln exhaust gas (19.15%), by radiation and convection from oven surfaces (15.11%) and finally hot air leaving through the refrigerator (5.61%). For the first two losses, a conventional system WHRSG (Waste Heat Recovery Steam Generator) was proposed, which would recover 1 MW of power according to the calculations. For the losses from the heat transfer surface in the furnace, a secondary shield system has been proposed. It is believed that the use of this system would save 3 MW of power. Thus, the total estimated savings for the entire system was about 4 MW, which indicated a 15.6% energy recovery of the total input power.

### 3. METHODOLOGY

The cement manufacturing process occurs mainly by two pathways: wet and dry. Both, Brazil and the world, use today the dry process, because it is more efficient from the energy point of view, since it is not necessary to spend energy to evaporate the water present in the wet process. Fig. 1 summarizes the main stages of the cement manufacturing dry process.

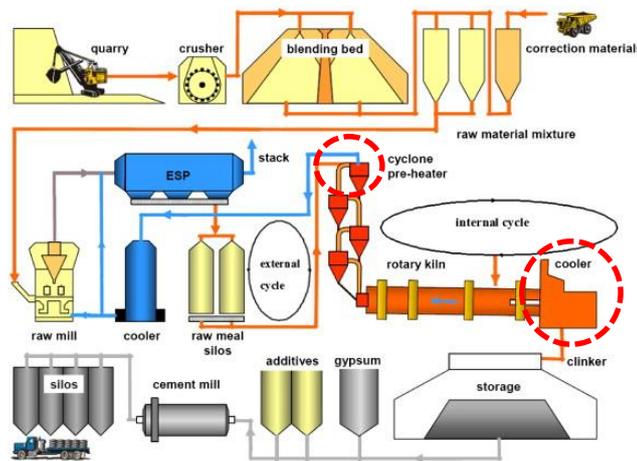


Figure 1. Stages of the cement manufacturing process.

Firstly, are crushed the stones and the limestone, to then grind it and mix it with the clay. After that, the mixture (or raw material) passes through an oven at a temperature up to 1450°C, which transforms the or raw material into clinker in the form of pellets. Soon after this process, the clinker, still glowing, is rapidly cooled, then grounded until it becomes dust. After this procedure, other materials are added to give the final configuration of the existing cement varieties.

We can also see the boundaries of the two discontinuous red line circles in Fig. 1, the two points of possible energy recovery by waste heat. They are the exit from the cyclone preheater and the exit clinker cooler. To use this energy, it is necessary the thermodynamic characterization of as these flows, specifically, about the mass flow, temperature, pressure and chemical composition. That is, you must know the energy quality of the flow in these two points.

It is important to emphasize that the residual heat of the clinker cooler is not available in all plants, since, in the most modern and efficient processes, this energy is already directed to the oven in the form of hot air to reduce fuel consumption. In such cases, the oven is called satellite oven and due to the use of this power, the only power available to cogeneration is the cyclone preheater.

For the development of the calculation work, an interactive spreadsheet allowing the estimation of the power that can be generated in a cement plant from the heat available at the output of the clinker cooler and pre-cyclone outlet was developed. For the calculations of these two parameters, it was necessary to characterize thermodynamically the gas flow

in those two points, namely, the temperature and gas flow in the pre-cyclone, temperature and gas flow in the clinker cooler and the specific heat of flue gas used in the process. In addition, it used the clinker production capacity per day.

The parameters mentioned above are shown in Tab. 1, with values taken from previous studies. These sources make up the sample of this study, which includes plants with production capacity of 3000-6300 tc/day.

Table 1. Features of gas from the preheater and the cooler in cement factories.

| Source                   | Production (tc/day) | Preheater       |             | Clinker Cooler  |             |
|--------------------------|---------------------|-----------------|-------------|-----------------|-------------|
|                          |                     | Temperature (K) | Flow (kg/s) | Temperature (K) | Flow (kg/s) |
| Mirolli (2006)           | 3,000               | 658.15          | 76.50       | 633.15          | 33.16       |
| ECRA (2009)              | 3,000               | 648.15          | 76.71       | 553.15          | 57.53       |
| Apodi (2016)             | 3,500               | 583.15          | 88.00       | 713.15          | 48.10       |
| Sui (2014)               | 4,500               | 588.00          | 113.20      | 613.15          | 56.25       |
| Wang, Dai and Gao (2009) | 5,000               | 613.15          | 126.70      | 583.15          | 86.20       |
| Kalex LLC. (2010)        | 6,300*              | 613.15          | 159.00      | 573.15          | 126.10      |

By not having the information of the chemical composition of the combustion gas in each cement plant, it is defined as a generic value, the specific heat at constant pressure of 1,005 kJ/kg.K, which is the value for air.

Thus, providing the available energy for cogeneration, and knowing the type of the heat recovery cycle to be used, there is an analysis table comprising thermal efficiencies according to the thermodynamic cycle used. The values of efficiencies were selected according to the authors Wang, Dai and Gao (2009) and can be chosen by the user as appropriate to their specific process. In order to simplify the use of the user interface, it has been created a cell with pre-defined values of specific heats at constant pressure for various types of combustion gases, according to Moran et al. (2013, p.793). Then it offers the choice of processing with a satellite oven or not. For this, there is another cell in the spreadsheet that allows the user to choose between the options "process with satellite oven" or "no satellite oven process", where the first option returns the zero value to available power cogeneration in the cooler. Figure 2 below brings illustration of interactive spreadsheet with sample one performed during the work-study.

| Gás do resfriador |                                |
|-------------------|--------------------------------|
| Vazão             | 126,10 (kg/s)/(t_clinker/dia)  |
| Vazão/Capacidade  | 0,02002 (kg/s)/(t_clinker/dia) |
| Temperatura       | 300 °C                         |

| Gás do pré-ciclone |                                |
|--------------------|--------------------------------|
| Vazão              | 159,00 (kg/s)/(t_clinker/dia)  |
| Vazão/Capacidade   | 0,02524 (kg/s)/(t_clinker/dia) |
| Temperatura        | 340 °C                         |

| Temperatura do Gás na Chaminé |        |
|-------------------------------|--------|
| Aquecedor                     | 228 °C |
| Resfriador                    | 114 °C |

| Calor Específico |               |
|------------------|---------------|
| Ar - 1,005       | 1,005 kJ/kg°C |

| Energia Disponível |             |
|--------------------|-------------|
| Qpré_ciclone       | 17897,04 kW |
| Qresf_clinker      | 23571,87 kW |
| Qttotal_disponivel | 41468,91 kW |

| Ciclo   | Eficiência - η (%) | Potência gerada (kW) | Comentários:              |
|---------|--------------------|----------------------|---------------------------|
| Rankine | 25,7               | 10657,51             | Single flash cycle        |
|         | 24,9               | 10325,76             | Dual-pressure steam cycle |
| Kalina  | 24,1               | 9994,01              |                           |
| CRO     | 20,6               | 8542,60              |                           |

| Capacidade de produção |                      |
|------------------------|----------------------|
|                        | 6300 (t_clinker/dia) |

Processo sem Forno satélite

Figure 2. Interactive spreadsheet in Portuguese interface with calculation examples.

### 3.1 Modeling of thermodynamic cycles

The single flash steam power cycle is based on the property that a certain mass of steam can be separated from water at saturated state if the pressure is lowered. The amount of flashed steam depends on the pressure before the flash tank and the final pressure in the flashing tank. The lower the pressure in the flashing tank the higher is the amount of steam, but on the other side, low pressure steam generates less power. Figure 2 (A) shows the configuration of single flash steam cycle in the cement plant. The working fluid that passed through feed pump is sent into the AQC boiler and preheated first. One part of the preheated working fluid is vaporized and superheated in AQC boiler, and another part of the preheated working fluid is sent to SP boiler to be vaporized and superheated. The two streams of superheated vapor from AQC boiler and SP boiler are mixed and expanded through the turbine to generate power. The rest of preheated working fluid is expanded in the flasher and separated into saturated vapor and saturated water. The saturated vapor is sent into the turbine to generate power. The turbine exhaust is condensed in the condenser, and passes through the condensing pump to be mixed with saturated water from the flasher.

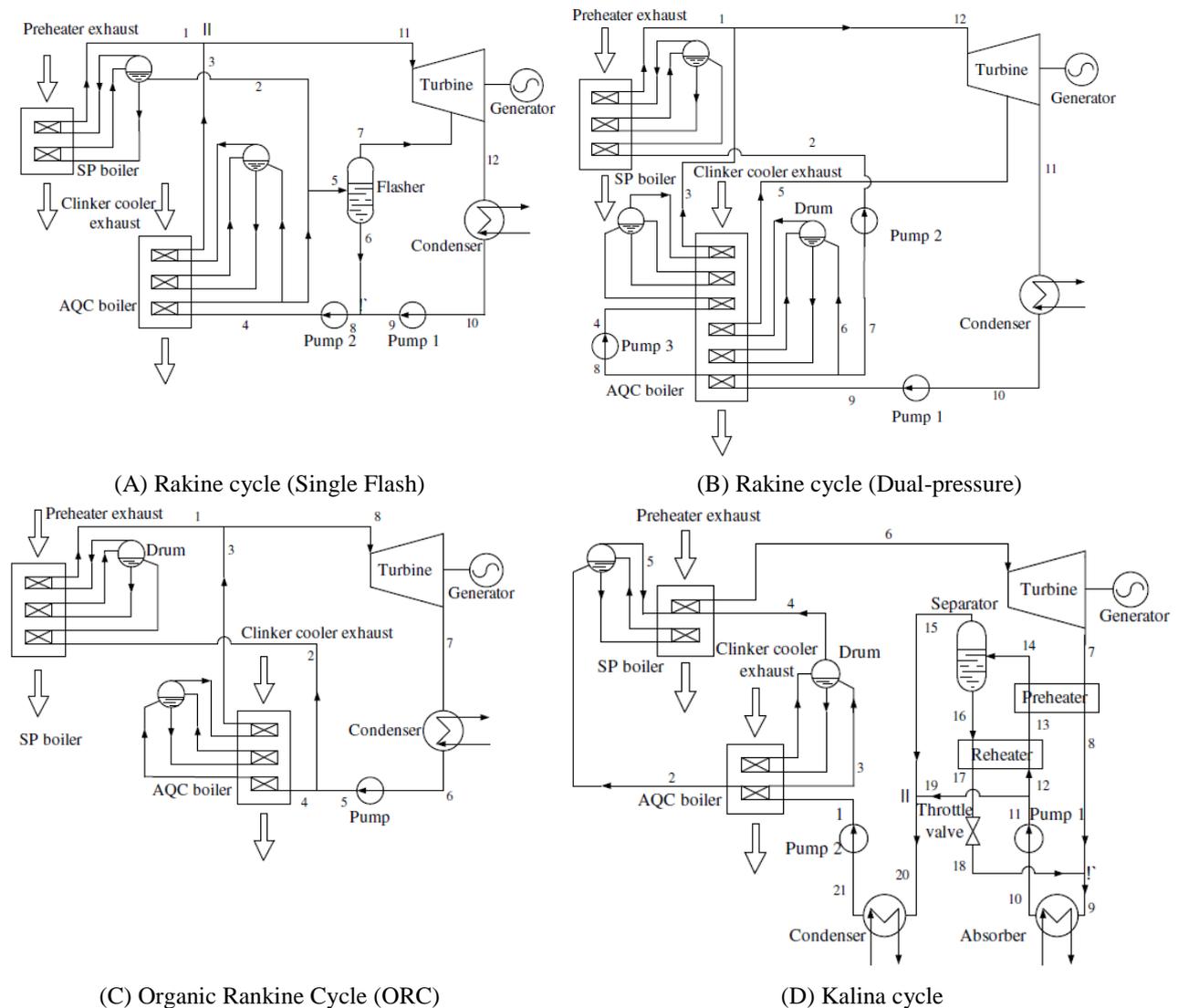


Figure 2. Thermodynamic cycles considered in the analysis.

Source: WANG; DAI and GAO, 2009

The dual-pressure steam cycle is superior to the single pressure steam cycle to make the best of middle and low temperature waste heats from the preheater exhaust and clinker cooler exhaust gases. Figure 2 (B) illustrates the dual-pressure steam cycle in the cement plant. The working fluid passing through the low pressure feed pump is sent into AQC boiler and preheated first. One part of the preheated working fluid is vaporized and superheated in AQC boiler, and the produced low pressure vapor is sent to the turbine to generate power. One part of the preheated working fluid passes through the high pressure pump and is vaporized and superheated in AQC boiler. The rest of the preheated working fluid passes through the high pressure pump and is sent to SP boiler to be vaporized and superheated. The two streams of high pressure superheated vapor from AQC boiler and the SP boiler are mixed and expanded through the turbine to generate power. The turbine exhaust is condensed in the condenser and sent to the low pressure feed pump.

The ORC is superior to the conventional Rankine cycle in recovering low-grade waste heat. In the present study, R123 as the working fluid is used to simulate the ORC. Figure 2 (C) shows the ORC in the cement plant. The organic working fluid passing through the feed pump is separated into two streams. One stream is sent into the AQC boiler to be preheated, vaporized and superheated. The other stream is sent to the SP boiler to be preheated, vaporized and superheated. These two streams of superheated vapor from AQC boiler and SP boiler are mixed and expanded through turbine to generate power. The turbine exhaust is condensed in the condenser and sent to pump.

Kalina cycle uses ammonia–water mixture as the working fluid, which exhibits variable boiling temperatures during the boiling process. This allows a small temperature difference for a good thermal match between the variable temperature heat sources and the working fluid, and consequently reduces irreversibility loss in the heat addition process. Figure 2

(D) illustrates the Kalina cycle in the cement plant. An ammonia–water working fluid is preheated in the AQC boiler, and vaporized in both SP boiler and AQC boiler, and superheated in SP boiler. Superheated ammonia–water vapor is then expanded through a back pressure turbine to generate power. The turbine exhaust is cooled, diluted with ammonia–poor liquid, and condensed in the absorber by cooling water. The saturated liquid leaving the absorber is compressed to an intermediate pressure, and most of the diluted liquid is partially boiled in the preheater and sent to the vapor separator. The saturated mixture is separated into an ammonia–poor liquid and an ammonia–rich vapor in the vapor separator. The ammonia–poor liquid is cooled and depressurized in a throttle valve, and the ammonia–rich vapor is mixed with some of the diluted liquid to obtain the working fluid. Then, the working fluid is condensed in the condenser and pumped to AQC boiler.

For the characterization of the thermodynamic cycle, calculations we carried out based on thermodynamics principles. To calculate the energy available in the pre-cyclone it is used Eq. (1), while the energy available in the clinker cooler was found from Eq. (2). The total energy available for cogeneration was calculated by Equation (3) and, finally, it was possible to reach the power produced by using Eq. (4):

$$Q_{PC} = \dot{m}_{PC} \cdot c_p \cdot (T_{PC} - T_{stack}) \quad (1)$$

$$Q_{resf} = \dot{m}_{resf} \cdot c_p \cdot (T_{resf} - T_{stack}) \quad (2)$$

$$Q_{total} = Q_{PC} + Q_{resf} \quad (3)$$

$$W_{prod} = \eta_{cycle} \cdot Q_{total} \quad (4)$$

Where, in equations 1 to 4,  $Q_{PC}$  is the thermal energy available for cogeneration in the pre-cyclone in kW;  $Q_{resf}$  is the thermal energy available for cogeneration in the clinker cooler, in kW;  $Q_{total}$  is the total energy available for cogeneration, in kW;  $W_{prod}$  is the electric energy produced from cogeneration, in kW;  $\dot{m}_{PC}$  is the gas flow in the pre-cyclone, in kg/s;  $\dot{m}_{resf}$  is the gas flow in the clinker cooler, in kg/s;  $c_p$  is specific heat at constant pressure combustion gas in kJ/kg°C;  $T_{PC}$  is the gas temperature in the pre-cyclone, in °C;  $T_{resf}$  is the gas temperature in the clinker cooler, in °C;  $T_{stack}$  is the gas temperature at the stack, in °C;  $\eta_{cycle}$  is the cycle thermal efficiency.

### 3.2 Cost analysis

The investment costs in the system to be deployed are mainly influenced by its location. Like many products, equipment for the installation of the system of waste heat recovery has a variable cost depending on the location of the plant, access to raw materials, and local market value of the currency in relation to the international market, among others. The IFC (2014) displays a graph that compares the installation cost in plants located in Asia, Europe and China, as we can see in Fig.3. The cost of specific equipment of the cogeneration system, which goes from China to these places, is represented in blue, while beige represents the cost related to the local scope of supply, such as material, transportation, labor, etc.

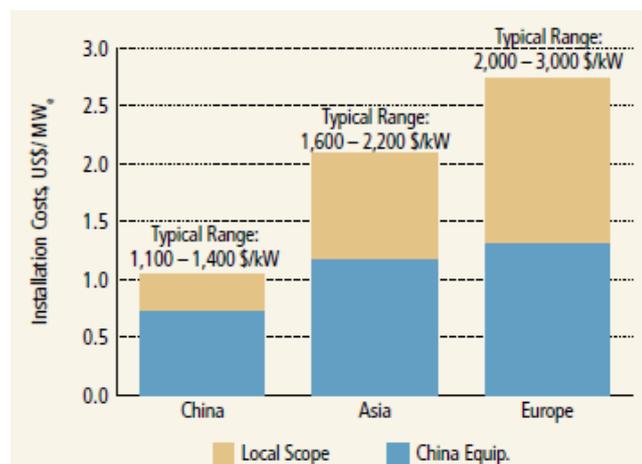


Figure 3. Chinese-manufactured WHR Equipment Installation Costs.  
Source: IFC 2014.

The sum of these amounts is the total investment cost. Thus, for calculation comparison, it applied the worst case of this chart, which is in the range between 2000 and 3000 US\$/kW. The exchange rate used in the calculations was 3.55 R\$/US\$ (in 05.04.2016).

#### 4. RESULTS ANALYSIS

From the results obtained, a table has been developed in order to organize and compare the results. Table 2, shown below, brings the cogeneration power estimate (kW) on the basis of production capacity (tc/day) of cement shown in previous chapters. Furthermore, it is also shown the installation cost of these technologies used for recovery.

Table 2. Cogeneration estimate and Installation Cost

| Production capacity (tc/day) | Co-generated energy (kW)   |                             |         |         | Installation Cost <sup>1</sup> (R\$) |                              |
|------------------------------|----------------------------|-----------------------------|---------|---------|--------------------------------------|------------------------------|
|                              | Rankine<br>Single<br>Flash | Rankine<br>Dual<br>Pressure | Kalina  | ORC     | Minimum cost<br>2000 US\$/kW         | Maximum cost<br>3000 US\$/kW |
| 3000 (Mirolli,2006)          | 5209.06                    | 5046.91                     | 4884.76 | 4175.35 | 36,984,326                           | 55,476,489                   |
| 3000 (ECRA, 2009)            | 5379.13                    | 5211.69                     | 5044.25 | 4311.68 | 38,191,823                           | 57,287,734                   |
| 3500 (Apodi, 2015)           | 6256.35                    | 6061.6                      | 5866.85 | 5014.82 | 44,420,085                           | 66,630,127                   |
| 4500 (Sui, 2014)             | 7468.87                    | 7236.37                     | 7003.88 | 5986.72 | 53,028,949                           | 79,543,423                   |
| 5000 (Wang, 2009)            | 8247.53                    | 7990.803                    | 7734.07 | 6610.86 | 58,557,505                           | 87,836,257                   |
| 6300 (Kalex LLC, 2010)       | 10657.51                   | 10325.76                    | 9994.01 | 8542.6  | 75,668,321                           | 113,502,481                  |

<sup>1</sup> The values of this column have been calculated for the extreme case, in other words, to higher energy cogeneration in their production capacities.

An analysis of Table 2 shows that, for the study of Mirolli (2006), the single flash Rankine cycle was what had the highest energy cogeneration with a generated power of 5209.06 kW, while the lowest was the cogeneration Organic Rankine cycle, which obtained 4175.35 kW of co-generated power. This is due to the fact that the efficiencies of these two cycles are the highest and lowest, respectively, among the efficiencies of available cycles. It can be observed that for two plants with the same production capacity, the co-generated power is practically the same. Taking as example the single flash Rankine cycle, in the example by Mirolli (2006), where the cogeneration power was 5209.06 kW and ECRA (2009), where the cogeneration power was 5379.13 kW. This small difference in values is also perceived in the three cycles.

As in previous examples, in the study by Apodi (2016), the cycle with the highest energy cogeneration was the Rankine and the lowest was the ORC. However, there is a considerable increase in these values over the first two examples. This can be explained due to an increase of 500 tc/day in the Apodi production capacity in relation to the other two studied plants.

As seen in the previous example, an increase in clinker production capacity caused an increase in the generated power estimation. The same happened in the case of Sui (2014), where a difference of 1,000 tc/day, caused an increase of about 1100 kW in the previous case. The most cogeneration cycle for this example was, again, the single flash Rankine, co-generating 7468.88 kW; and the lowest was the ORC, co-generating 5986.72 kW.

Wang's (2009) example again confirms that an increase in clinker production capacity generates an increase in the cogeneration power plant. Furthermore, by comparing them with the results others have shown, Table 7 shows that a link exists between the increase of production capacity and cogeneration power, since, for each portion 500 tc/day is increased, the co-generated power increases approximately 700 kW. In Wang's study (2009), again the largest cogeneration Rankine cycle was the single flash, co-generating 8247.54 kW; and the lowest was the ORC, co-generating 6610.87 kW.

Finally, in Kalex LLC's example (2010), as well as all other examples, the single flash Rankine cycle is the largest cogeneration cycle, with a cogeneration of 10657.51 kW; while the shortest cycle cogeneration was the ORC, with a cogeneration of 8542.60 kW. For a better comparison between results, we generated Fig. 4 shown below.

Doing the picture analysis, we see that the results almost respect a linear function that governs the energy cogeneration due to the clinker production capacity. It is also noted that the Rankine cycle (Single Flash) was the one with the high cogenerated power in all six studies, whereas the ORC was what had the lowest value. This fact can be explained by the efficiency of each one of these cycles. The two line limits (lower and upper) shown in the diagram were based on the literature, according to One Stone based Research (IFC, 2014), and represent the expected range of cogeneration for a given production capacity of the plant. You can see that the results of this study are within the results expected by the theory.

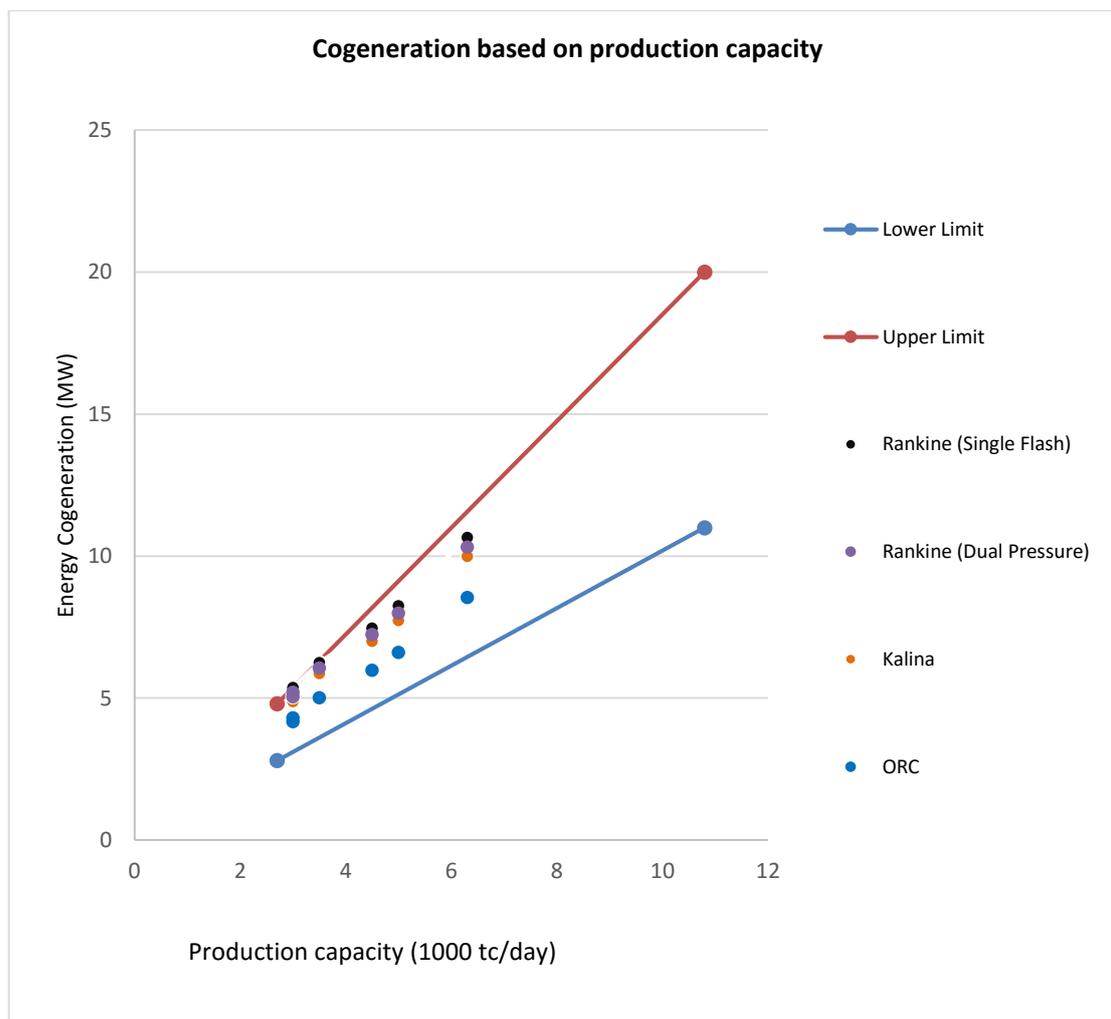


Figure 4. Cogeneration based on production capacity.

## 5. CONCLUSION

From the present study, we identified the preheater and clinker cooler as sources for waste heat recovery and electricity generation. Thus, from the estimate, the cogeneration potential for the different technologies of waste heat recovery, the single-flash Rankine cycle, which showed greater efficiency, was the one with the highest values for the data used from different authors cited in this study.

However, in the Kalina cycle, the possibility of varying the concentration of working fluid, which is an ammonia-water binary mixture in cycle, allows raising its efficiency and applying it to real situations in the industrial field. Therefore, it is understood the need for new studies, comparing the actual application of these technologies in cement industries.

Furthermore, it is possible to conclude that the installation cost of the cogeneration system is justified by the potential values generated and the representativeness of the electricity cost in a company. This investment can be calculated, planned and becomes more significant with the increasing cement production capacity, since it is directly proportional to the clinker production capacity.

Finally, it was concluded that the Brazilian cement sector may use cogeneration technology, since the results confirm the efficiency of the cogeneration system used in cement factories.

## 6. ACKNOWLEDGEMENTS

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