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ECOLOGICAL EFFICIENCY ANALYSIS OF A COMBINED CYCLE POWER PLANT CONSIDERING THE CHEMICAL CAPTURE OF CO_2

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Abstract. *The generation of electricity by thermoelectric power plants is very important to Brazil. The use of natural gas in combined cycle power plants is the best alternative in the case of fossil fuels, but your combustion results in greenhouse gases emissions. In this paper is analyzed a combined cycle thermoelectric power plant with a 500 MW of capacity, considering the CO_2 capture and your influence in the ecological efficiency. This parameter uses the thermodynamic efficiency of the power plant and the pollutant indicator, as a function of the CO_2 equivalent and lower heat value (LHV) of the natural gas. The carbon dioxide capture is made by chemical absorption process of the exhaust gases from natural gas combustion. This paper presents an ecological efficiency analysis of a power plant integrated to a process of chemical absorption using aqueous solution of monoethanolamine as solvent, that include carbon dioxide compression, absorbent column with inter-cooling and a stripper column with mechanical vapor recompression process with low carbon dioxide ratio, for decrease the penalties in the power plant efficiency. As conclusion, the CO_2 capture process promote changes in the electrical and ecological efficiencies of the power plant, decreasing about 6.7 % and increasing 7.56%, respectively.*

Keywords: *power plants, combined cycle, ecological efficiency, carbon dioxide capture, pollutant indicator.*

1. INTRODUCTION

1.1 The global warming situation

Although there is no universal agreement about the cause, there seems to be a growing acceptance that there is a global climate change, and many scientists believe that a leading cause is the anthropogenic emissions, that is, derived from human activities, gases that aggravate the greenhouse effect in the atmosphere.

The thermoelectric plants fueled by fossil fuels, natural gas in the case of this study, are considered a main source of energy in the world. However, the fossil fuel combustion invariably has as product the carbon dioxide, considered the main cause on the greenhouse effect, causing global warming. Thus, there is increased research and given a particular emphasis on search for more effective methods to capture CO_2 emissions from power generation plants. Due to the effect of CO_2 emissions on global warming, many countries begin to impose taxes or regulations on the amount of CO_2 that is emitted into the atmosphere.

The CO_2 capture in power plants is based on the separation of the fuel or exhaust gases carbon. There are several processes for recovery of CO_2, such as chemical absorption, adsorption, membrane separation and cryogenic. For CO_2 capture and post-combustion technologies in a plant to natural gas, chemical absorption, the use of amine solutions is the technology the lowest term financial return according to the report of the IEA (IEA, 2008). According to Gaspar and corms (2012), aqueous solutions of monoethanolamine (MEA) are considered the best solvent solutions among the most studied amines. In post-combustion capture the CO_2 is removed after combustion of fossil fuel, namely carbon dioxide is captured from the flue gases in thermoelectric power plants and other large point sources. The technology is well understood and it is currently used in other industrial applications, though not to the same degree that it may be necessary for a power plant of the same size power.

2. MATERIAL AND METHODS

2.1 Power plant of this study

The power plant studied in this work, showed in the Fig. 1, basically consists of two gas turbines, two heat recovery steam generators and a steam turbine, with a total capacity of 500 MW. In this cycle, natural gas comes through pipelines, from Mexilhão Field, from the natural gas base of Caraguatatuba, which will be directed to gas preheaters before entering the combustion chambers where the gas is mixed with air that had been compressed by the compressor after passing through the dehumidifiers. The product of combustion from this natural gas is expanded in the gas turbine that is coupled by a shaft to the compressor and a generator, providing mechanical energy to them. The exhaust gases from the gas turbine pass through a heat recovery boiler, which is fed with water through a pump. The water is vaporized til the level of superheated vapor and is extracted by two lines to the turbine steam where there are three stages, one for high pressure steam and two low pressure steam, in the high pressure steam stage there is an extraction that returns to the heat recovery boiler, where it is reheated and used at low pressure steam lines. In all three stages of the turbine, the steam is expanded and outlet a mixture of liquid and vapor which is directed to a condenser, fed by demineralised water at 24 °C from the cooling tower and returns increased by 12 °C, thereby the mixture arising from the steam turbine is converted into saturated liquid that is pumped and returns to the heat recovery boiler, thus completing the cycle.

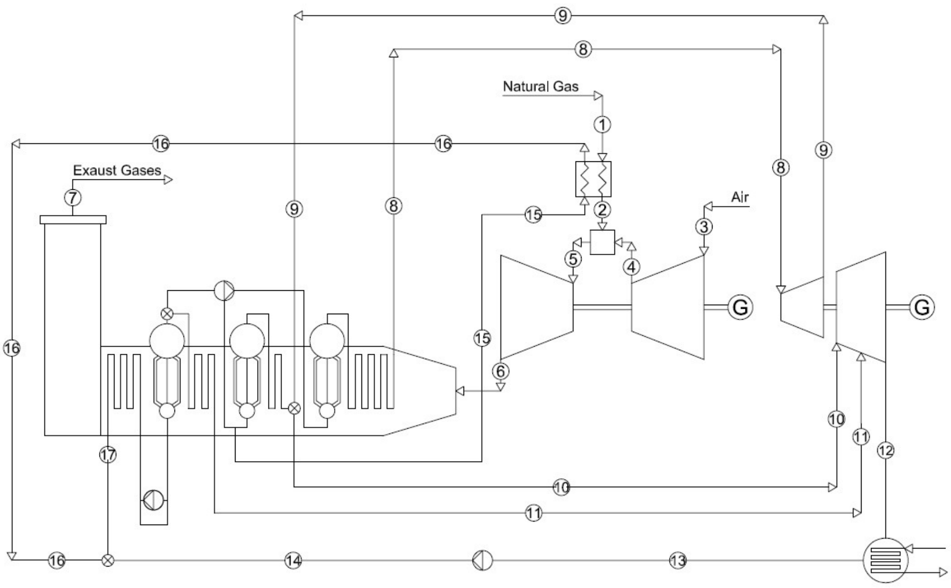

Fig. 1 - Power plant basic scheme

The points highlighted in Fig. 1 are shown in Tab. 1 and Tab. 2. These values were used for calculating the energy efficiency of the plant through an analysis using the first law of thermodynamics, dividing the two cycles (Brayton and Rankine) which are combined to compose thermoelectric plant studied in this work.

Table 1. Points of the Brayton cycle

Point	*p (MPa)*	*T (°C)*	*ṁ (kg/s)*
1	0.1	25	18.22
2	0.1	185	18.22
3	0.1	25	787.88
4	1.381	379	787.88
5	1.312	1320	806.10
6	0.1	612	806.10
7	0.1	86	806.10

Table 2. Points of the Rankine cycle

Point	*p (MPa)*	*T (°C)*	*ṁ (kg/s)*	*h (kJ/kg)*	*s (kJ/kg/K)*
8	13.1	566	96.36	3511	6.652
9	2.701	340	96.36	3098	6.702
10	0.3351	292	13.67	3052	7.621
11	2.413	566	110.44	3610	7.523
12	0.00728	40	124.11	2358	7.565

13	0.00728	40	124.11	167.5	0.5723
14	14.01	42	124.11	188.2	0.5933
15	0.38	226	9.46	2915	7.307
16	0.38	44	9.46	184,6	0.6253
17	14.01	42	133.57	188.2	0.5933

2.1.1 Efficiency of the plant

The analysis on this topic demonstrates through the first law of thermodynamics the amount of heat and electricity generated by the thermoelectric plant investigated as well as its final electrical efficiency, this quantitative analysis is thus not be considered power quality. The first law analysis need to be divided into two stages, first the analysis of the Brayton cycle and then the analysis of the Rankine cycle is performed. In the first cycle, the two gas turbines were considered identical. Table 2 shows the fixed parameters adapted to the following analysis (Silveira and Tuna, 2003, 2004).

Table 2. Fixed parameters of efficiency

Parameter	Efficiency
η_{ISO_c}	0.82
η_c	0.86
η_{gt}	0.98
η_{st}	0.98
η_g	0.98
η_p	0.9

The mechanical work consumed by the compressor can be defined by the Eq. (1).

$$\dot{W}_c^{mec} = \frac{\dot{m}_4 \cdot \bar{c}_p^{3,4} \cdot (T_3 - T_4)}{\eta_c} \quad (1)$$

The mechanical energy generated by the gas turbine can be defined by the Eq. (2).

$$\dot{W}_{gt}^{mec} = \dot{m}_5 \cdot \bar{c}_p^{5,6} \cdot (T_5 - T_6) \cdot \eta_g \quad (2)$$

The electrical energy generated by the gas turbine cycle can be defined by the Eq. (3).

$$E_{gt} = \left(\dot{W}_{gt} - \dot{W}_c\right) \cdot \eta_g \quad (3)$$

The mechanical energy generated by the steam turbine can be defined by the Eq. (4).

$$\dot{W}_{gt} = [(\dot{m}_8 \cdot h_8) + (\dot{m}_9 \cdot h_9) + (\dot{m}_{10} \cdot h_{10}) - (\dot{m}_{11} \cdot h_{11}) - (\dot{m}_{12} \cdot h_{12})] \cdot \eta_{st} \quad (4)$$

The electrical energy consumed by the pump can be defined by the Eq. (5).

$$E_p = \frac{(\dot{m}_{13} \cdot h_{13}) - (\dot{m}_{14} \cdot h_{14})}{\eta_p} \quad (5)$$

The electrical energy generated by the steam turbine cycle can be defined by the Eq. (6).

$$E_{st} = \dot{W}_{st} \cdot \eta_g - E_p \quad (6)$$

The electrical efficiency of the plant can be defined by the Eq. (7). According to Santos et al. (2014), the energy provided by this fuel is 860,520.00 kW.

$$\eta_p = \frac{E_{gt} + E_{st}}{\dot{Q}_{fuel}} = 59.01\% \quad (7)$$

2.2 Carbon dioxide absorbtion

The absorption/stripping system can be placed at the end of new or existing natural gas fired power plants. Amine solvents are used since they react with CO_2 under certain conditions. A lean solvent (low CO_2 concentration) is fed into the top of the absorber. The solvent is counter currently contacted by flue gas containing CO_2. The CO_2 chemically reacts with the amine solvent and the treated gas exits the top of the absorber. This rich amine (high CO_2 concentrations) leaves the bottom of the absorber and is preheated by a cross exchanger before entering the top of the stripper. In the stripper, typically at a higher temperature and pressure than the absorber, the reaction between the amine and CO_2 is reversed which liberates CO_2 into a concentrated stream obtained at the top of the stripper. The lean solvent from the stripper undergoes heat exchange and goes back to the absorber to repeat the process. This process configuration is illustrated in Fig. 2, and combines the effect of inter-cooling of absorber column and the configuration of lean vapor recompression for to optimize the absorption system. The absorber and compression performances were controlled by adjusting the solvent circulation rate to meet 90% CO_2 capture ratio.

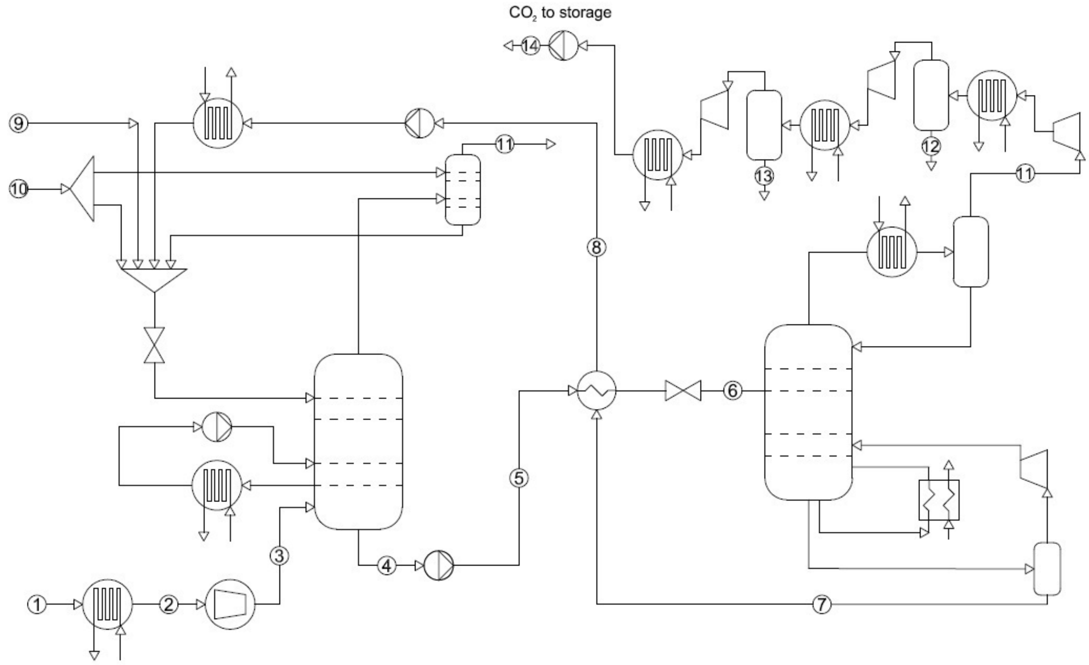

Fig. 2 - Absorption plant basic scheme

Table 3 shows the values used for calculations of energy use of the CO_2 absorption system that was adapted from Amrollahi et al. (2012).

Table 3. Points of the Absorption plant

Point	Temperature (°C)	Pressure (MPa)	Mass Flow (kg/s)	Mass fraction				
				CO_2	N_2	O_2	H_2O	MEA
1	86.00	0.10	806.10	0.0832	0.7376	0.1159	0.0633	0.0000
2	42.00	0.10	802.32	0.0836	0.7411	0.1165	0.0589	0.0000
3	48.40	0.11	802.32	0.0836	0.7411	0.1165	0.0589	0.0000
4	41.80	0.68	828.62	0.0953	0.0000	0.0000	0.6301	0.2747
5	93.00	0.64	828.62	0.0953	0.0000	0.0000	0.6301	0.2747
6	101.70	0.10	767.29	0.0451	0.0000	0.0000	0.6651	0.2897
7	50.30	0.60	767.29	0.0451	0.0000	0.0000	0.6651	0.2897
8	25.00	0.40	0.12	0.0000	0.0000	0.0000	0.0000	1.0000
9	25.00	0.40	9.37	0.0000	0.0000	0.0000	1.0000	0.0000
10	45.80	0.10	744.77	0.0064	0.7801	0.1483	0.0652	0.0000

11	24.90	1.10	61.33	0.9837	0.0000	0.0000	0.0163	0.0000
12	20.00	4.30	0.50	0.0049	0.0000	0.0000	0.9951	0.0000
13	20.00	18.90	0.10	0.0241	0.0000	0.0000	0.9759	0.0000
14	24.90	110.00	60.73	0.9992	0.0000	0.0000	0.0008	0.0000

The concept behind inter-cooling is to remove the heat generated by the exothermic absorption reaction and reduce the liquid temperature at the absorber bottom. Because of the exothermic nature of absorption reaction, there is an overall temperature increase in the absorber. Inter-cooling cause temperature reduction, which is in favor of higher driving force for the absorption process and increases the absorption capacity of the solvent, i.e. solvent rich loading. The purpose of vapor recompression designs is to provide steam that is regained from the stripping process as the heating media to the reboiler. One of the alternative designs of the vapor recompression model has been presented by Jassim and Rochelle (2005). In this design, the stripper bottom is used to intercool the gaseous stream in the multistage compressor. The purpose of the design is to recover the heat of condensation of the overhead water vapor and the heat of compression to re-boil the stripper. For the aforementioned design, the number of compression stages has been doubled. The results of this study show that the reboiler duty has been decreased by 43%, but the total work demand of the process stayed at the same level regarding the increased amount of CO_2 compression work.

2.2.1 Carbon dioxide absorption system energy use

In carbon dioxide absorption about 60% of the energy penalty is caused by the regeneration energy requirements of state-of-the-art technology, including CO_2 compression. Based on conventional MEA, Chakma and Tontiwachwuthikul (1999) claimed that the regeneration energy contributes 35–40% to the incremental cost of energy of the scrubbing systems. The energy consumption for regeneration can be split into three parts.

2.2.1.1 Energy required to reverse the chemical binding of CO_2 to the solvent

The energy required for the reversed reaction of CO_2 binding depends entirely on the solvent formulation. In this work is assumed conventional MEA solvents as a baseline, Rao et al. (2004) used 1.9 MJ/kg_{CO2} as the energy requirement for this reaction.

2.2.1.2 Energy required to heat the solution

The general equation that is applicable for the amount of energy required to heat the solution is shown in Eq. (8):

$$\dot{Q} = c \cdot m_s \cdot \Delta T \tag{8}$$

Where Q is the heat added, c the specific heat of the solution, m_s the mass of solution and ΔT is the change in temperature. Because we were specifically interested in the energy requirements per amount of CO_2, we needed to adjust the equation to the one shown in the Eq. (9):

$$Q_{CO_2} = c \cdot \frac{m_s}{m_{CO_2}} \cdot \Delta T \tag{9}$$

From Eq. (9), it is clear that the most important parameter is the amount of CO_2 handled per kilogram solution in each cycle.

2.2.1.3 Water evaporation

The amount of water evaporated per mole CO_2 extracted in the stripper is affected by CO_2 loading and the stripping temperature. Although water evaporation in the stripper is responsible for a relatively large share of the energy requirements, hardly any information has been presented in the literature. In 1995, Feron and Jansen (1995) stated that, in state-of-the-art MEA processes, 1–2 moles of water are evaporated for each mole CO_2 captured, which corresponds to an energy consumption of 0.93–1.85 MJ/kg CO_2. The number of moles of water evaporated per mole CO_2 in an IEA study (IEA GHG, 2000) was between 0.72 and 0.76, corresponding to an energy consumption of about 0.7 MJ/kg CO_2. We used this number as our medium-term value.

2.2.1.4 Stripper optimized system consumption

In this case, according to Amrollahi et al. (2012), reboiler heat consumption is 2.71 MJ/kg$_{CO2}$. The addition of vapor compressor increased the work for the blower and compressors, but the total work demand of the capture and compression plants decreased. But with a real consumption 0.65 MJ/kg as compared to heat/energy in this case is 0.24.

2.2.1.5 CO_2 compression

The CO_2 compression energy requirements should be calculated like showed in the Eq. (1), but first using the Eq. (10) is important to calculate temperature of the CO_2 after the compression and before the inter-cooling.

$$T_{out} = T_{in} \cdot \left\{1 + \frac{1}{\eta_{ISO_c}} \cdot \left[\left(\frac{p_{out}}{p_{in}}\right)^{\frac{\delta-1}{\delta}} - 1\right]\right\} \tag{10}$$

2.2.2 Efficiency penalty caused by the carbon dioxide plant

When the chemical absorption CO_2 capture and compression plants are integrated into a power plant, there are several associated power losses at different points of the process. These energy penalties are related to mechanical work demand of blower and several pumps/compressor in the capture plant, the steam turbine power reduction due to steam extraction to provide the reboiler steam-need for the stripper column, and the mechanical work demand of the compressors to compress captured CO_2 to a certain transport/injection pressure.

$$\eta_{ccs}^{CO_2} = \frac{\left[\left(\dot{W}_{gt}^{mec} - \dot{W}_{c}^{mec}\right) \cdot \eta_g + \left(\frac{\dot{W}_{st}^{mec}}{\eta_{st}} - Q_{stripper}^{CO_2}\right) \cdot \eta_{tv} \cdot \eta_g - \dot{W}_{p}^{ele}\right] - \left(\dot{W}_{blower}^{mec} + \dot{W}_{c,CO_2}^{mec}\right)}{\dot{Q}_{fuel}} = 52{,}31\ \% \tag{11}$$

2.3 Pollutant emissions and ecological efficience

According Brizi and Silveira (2014), the natural gas is cleaner than fossil fuel oil or coal burning power, it is believed that the natural gas provides part of the solution to climate change and the problems associated the poor air quality. Once considered, in large part, a residual product from oil production, the use of natural gas is currently experiencing enormous increase in demand worldwide. As an economically viable and less polluting abundant fuel, natural gas makes sense for developing economies in search of new sources of energy. Unlike coal and oil, natural gas has a hydrogen/carbon higher ratio and emits less carbon dioxide for a given amount of energy consumed. As the cleanest burning fossil fuel, natural gas offers an effective means in terms of immediate cost to improve air quality. Unlike coal and oil, natural gas releases virtually no particulate matter in the atmosphere, which prevents photosynthesis in plants and aggravates heart and lung disease in humans. Particulate matter is also a contributor to smog. The production and the burning of fossil fuels leads to emissions of nitrogen oxides and sulfur oxides; nitrogen oxides result in many environmental impacts, including pollution and acid rain. Sulfur oxides also contribute to acid rain.

The purpose of this item is to determine the rates of emissions in tons/year of CO_2, NO_X, SO_2 and PM of the thermoelectric plant selected. In the second stage, is to determine how these pollutants affect the environment by calculating the ecological efficiency. The ecological efficiency assesses how polluter is a thermoelectric plant, considering the combustion of one kg of fuel, and not the amount of gases released per unit of energy generated. The general chemical formula for combustion of natural gas is described below in Eq. (12) (Villela and Silveira, 2007). This equation determines the emission of CO_2, NO_x, Particulate Matter (PM) and SO_2.

$$r_1CH_4 + r_2C_2H_6 + r_3C_3H_8 + r_4C_4H_{10} + r_5CO_2 + r_6N_2 + r_7O_2 + r_8N_2 \rightarrow p_1CO_2 + p_2H_2O + p_3N_2 + p_4O_2 \tag{12}$$

Eq. (13) can determine the value of the molar mass of the natural gas to be considered in this study:

$$M = 16 \cdot r_1 + 30 \cdot r_2 + 44 \cdot r_3 + 58 \cdot r_4 + 44 \cdot r_5 + 28 \cdot r_6 \tag{13}$$

The values of the resulting products of combustion of 1 kg of natural gas can be calculated considering the following emissions shown below in Eq. (14), (15) and (16) (Villela and Silveira 2007; Carvalho Jr and Lacava, 2003):

CO2 Emissions:

$$m_{CO_2} = \frac{(p_1 \cdot 44 \cdot 2)CO_2}{M} \tag{14}$$

NO_X Emissions:

$$m_{NO_x} = \frac{\frac{(2{,}270 \cdot 22.4 \cdot 10^{-3})NO_X}{10^6}}{M \cdot 10^{-3}} \tag{15}$$

Particulate matter emissions:

$$m_{MP} = \frac{(240 \cdot 22.4 \cdot 10^{-3})PM}{M \cdot 10^{-3}} \tag{16}$$

From these data, the emission of carbon equivalent can be obtained by Eq. (17).

$$(CO_2)_e = (CO_2) + 80 \cdot (SO_2) + 50 \cdot (NO_x) + 67 \cdot (PM) \tag{17}$$

The Tab. 4 shows the values of the resulting products of combustion:

Table 4. Resulting products of combustion

Emission	Result without CCS [kg/kg$_{NG}$]	Result with CCS [kg/kg$_{NG}$]
CO_2	2.703	0.27
NO_X	3.124 x 10-3	3.124 x 10-3
Particulate Matter	3.303 x 10-4	3.303 x 10-4
$(CO_2)_e$	2.88	0.29

Cardu and Baica (1999) analyzed the environmental impact of emissions from gas-fired combined cycle, in other words, associations of plants with gas turbines with steam turbines operating in cogeneration system and using fuels: coal, oil and diesel natural gas. In this analysis, is considered emissions of carbon dioxide, nitrogen oxides and sulfur dioxide; furthermore, a comparison of concentrations of each compound of the exhaust gases with specific regulatory standards.

The best fuel from an ecological perspective is the one submitting a minimal amount of carbon dioxide equivalent $(CO_2)_e$ obtained from burning of it. To quantify this environmental impact defines as "pollution indicator" (Π_g).

Ecological efficiency (ε) is a dimensionless indicator to assess the environmental impact of exhaust emissions from a thermal power plant, by comparing emissions of pollutants integrated hypothetically (equivalent CO_2) with existing standards of air quality. It is considered the pollution indicator as a determining factor on the ecological efficiency, expressing an energy based emissions indicated by a fractional number (Cardu and Baica, 2001). Pollution indicator by (Cardu and Baica, 1999; Villela and Silveira, 2006) and ecological efficiency by (Cardu and Baica, 2001; Villela and Silveira, 2007) are defined by the Eq. (18) and (19).

$$\Pi_e = \frac{(CO_2)_e}{Q_{fuel}} \tag{18}$$

The pollution indicator is a variable which measures the amount of pollution expressed in kg/MJ, that is, measures the amount of pollution in an energy basis.

$$\varepsilon = \sqrt{\frac{0.204 \cdot \eta_p}{\eta_p \cdot \Pi_g} \cdot (\ln 135 - \Pi_g)} \tag{19}$$

The results of the pollutant indicator and the ecological efficiency for the power plant without CCS and with CCS are showed in the Fig. 3, a graphic that illustrates the differences between both.

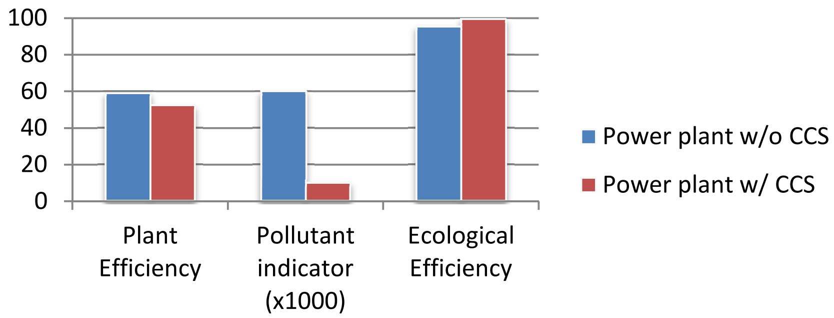

Fig. 3 - Results of the efficiencies

The following Table 5 shows the estimated mass in tones of pollutant gases, which are issued annually by the thermoelectric plant investigated, with and without the CO_2 capture, in steady state that operates 7200h per year.

Table 5. Calculated mass of pollutant gases per year

Pollutant Emission	Emissions without CO_2 capture(ton/year)	Emissions with CO_2 capture(ton/year)
CO_2	1,276,197.12	127,619.71.
NO_X	1,474.82	1,474.82
Particulate Matter	155.93	155.93
$(CO_2)_e$	1,360,385.29	211,807.88

3. RESULTS AND CONCLUSIONS

The analysis applied to a thermoelectric plant operating in combined cycle gas turbines with associated heat recovery without supplemental fuel burn and a condensing steam turbine. As expected, through energy analysis was possible to verify that the energy efficiency of the plant is in agreement with the literature studied. The thermoelectric of this study, without CO_2 absorption, has reached a 59.01% global efficiency and ecological efficiency of 95.23%. According to Villela and Silveira (2007), the natural gas has values of ecological efficiency between 91.6% and 95.4% for the system with and without supplemental firing systems respectively. With the CO_2 absorption systems, a decrease of the power plant efficiency to 52.31% was observed, but the ecological efficiency rose to 99.45%. Despite the positive results of this work, carbon dioxide absorption systems for chemical absorption are still very expensive, and it is recommended that must be made an economic analysis find out how this improvement in ecological efficiency affects the energy production cost.

4. ACKNOWLEDGEMENTS

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