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EXERGOECONOMIC AND EXERGOENVIRONMENTAL ANALYSIS OF POWER PLANT WITH CO2 CAPTURE AND STORAGE

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Abstract. *A natural gas combined cycle power plant (NGCC) with CO_2 capture and storage system (CCS) were investigated. The exergy, exergoeconomic and exergo-environmental balances were carried out using the specific Exergy Costing (SPECO) approach. The cost and environmental impact of NGCC, CCS, pipeline, storage and inputs were described.*

Results show that the CCS with sequestration of 90% CO2 reduces CO2 emissions at NGCC by 82%, however, other emissions and environmental impact of Natural gas, reduces the EI rate by 7%. The CCS trade-offs are a reduction of the net power and exergetic efficiency of 10%. Additionally the CCCS increased the specific cost and specific EI per exergy unit of electricity of 23% and 2%, respectively. The natural gas heater has the worth economic and environmenatl performance, due to its high cost and EI rate of exergy destruction on relation to its cost and EI of component. Its efficiency should be increased. Notwithstanding the combustor chamber and the super heater have higher EI. They should be reduce its efficiency or its EI of components at exergoenvironmental point of view.

Keywords: *Electricity, carbon capture and storage, exergoeconomy, exergoenvironmental analyses, eco-indicator 99.*

1. INTRODUCTION

The energy demand can be supplied by power plants. Its production should be sustainable, even thought, this system consumes fossil fuels which emits greenhouse gases (GHG), being very harmful to the environment and human health.

The main anthropogenic GHG emitted with fossil fuels is the carbon dioxide. CO_2, greenhouse gas has high contribution to the climate change. Several researchs have been developed to reduce CO2 emissions. A wide types of power plants, which reduction of the CO2 emitted and supply the energy demand have been developed. The carbon capture and storage (CCS) appear as a technically feasible alternative (Petrakopoulou, *et al,* 2017; Wennersten, *et al,* 2015).

The carbon capture and storage (CCS) approach is a technology to reduce CO_2 emissions. It consists of separating the CO_2 from industrial sources, transportation of it to a storage facility and its consequent isolation from the atmosphere (Wennersten , *et al*, 2015). There are many types of CCS technologies, which depending on the method and stage of extraction or the type of storage unit utilized, which is most commonly of geological nature, with the carbon dioxide placed in a rock formation with a few kilometers of depth. The different stages of extraction and their respective mechanism were explored in literature. They are divided in three types, which are, post-combustion (Andersson, *et al*, 2016; Luo and Xang, 2016), pre-combustion (Siefert, *et al*, 2016; Casero, *et al*, 2014) and oxy-combustion (Cormos, 2016; Gopan, *et al*, 2014). Moreover, several works (Wennersten, *et al*, 2015; Leung, *et al*, 2014) explained and outlined the characteristics, future perspectives and risks in the economic and social spheres for these CCS systems. In the current work the CCS arrangement is implemented in a combined power plant with a post combustion system and geological storage of carbon dioxide.

Natural gas is used in several processes and power generation cycles. Such processes are production of steam and heat, commercial heating and electricity generation. Regarding electricity, it is used in steam cycles, gas turbine and their combination, the natural gas combined cycle (NGCC). The NGCC is the one that has the highest efficiency, among others cited. For this reason, it has been increasingly used in industrial energy generation. Therefore, the implementation of a CCS system in these types of plants would provide a significant reduction in CO_2 emissions, the feasibility and environmental impact of such action has been deeply studied and investigated in several works (Cormos, 2015; El Nasr, *et al*, 2015; Zhu, *et al*, 2016).

When the CCS system is installed some additional costs of equipments, operation and maintenance of the system increase the electricity cost. Moreover, part of the previous net power is drained by the CCS arrangement. This system is analized by several authors in literature in different types of plants (Cabral, *et al*, 2017; Franz, *et al*, 2014; Ferrara, *et al*, 2017; Keohane, *et al*, 2017). The trade-offs are that the CO_2 capture unit has considerable energy demand and reduces the net electricity (Singh, *et al*, 2011). However, the system is responsible for the reduction in the CO_2 emissions and consequent mitigation of the climate change, leading the energy production towards a more sustainable path. The reduction in the carbon dioxide emissions can also aid financially through the generation and accumulation of carbon credits instituted by the Kyoto Protocol (Keohane, *et al*, 2017). The commercialization of these credits between companies and countries can assist to reduce the expenses and increase the economic profits. The environmental analysis and GHG reduction of many carbon capture schemes are also found in literature (Petrakopoulou and Tsatsaronis, 2014). Therefore, the balance between commercial and environmental elements is of primary importance in the implementation of a CCS system.

In this work the NGCC operating in Rio Grande do Norte/Brazil and CCS system as mitigation of CO_2 emissions are presented. Two methods have been analyzed: First, the exergoeconomy which combines exergy analysis with economic parameters and the second is exergoenvironmental analysis which applies environmental impact into exergy analysis. The installation, operating and maintenance costs will be take into account. Therefore, the specific contributions of this paper are to develop an exergy, exergoeconomic and exergoenvironmental model for power plant; to evaluate exergy rate and environmental impact per exergy unit of electrical power and calculate the effect of CCS at exergoeconomic and exergoenvironmental point of view.

2. SYSTEM DESCRIPTION

In order to model the energy and exergy balance, some real data of gas turbine and heat exchangers were taken based on site measurements and some assumptions are made as:

- The system is at steady-state and steady-flow
- The combustion of natural gas is complete,
- The efficiency in combustor is 98%.
- The pressure drops in all pipelines and heat exchangers are considered to be negligible.
- The electric generator efficiency is assumed as 98%.
- All heat exchangers were considered adiabatic.

Fig.1 shows a schematic diagram of the natural gas combined cycle power plant (NGCC) with the mitigation system CCS.

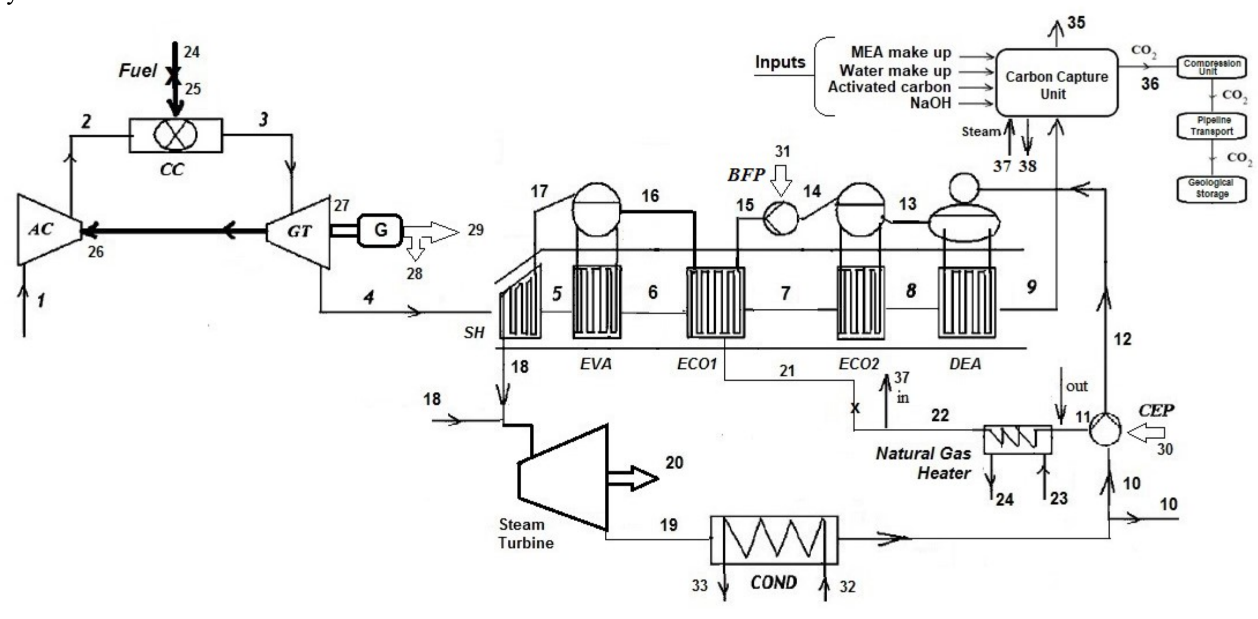

Figure 1 – Schematic diagram of the power plant with CCS system with CCS system.

This power plant with two gas turbine is located in the northeast of Brazil. Each gas turbines produces 150 MW of electricity. This system produces steam which can be used in a steam turbine to generates 100 MW of power and the global power production is of 400 MW. The exhaust gases leave the cycle at 128 °C and a mass flow rate of air is 411.5 kg/s.

The description of power plant is: The environmental air is drawn into air compressor (AC) where increases the temperature and pressure of air. The compressed air enters the combustion chamber (CC) and fuel is burned, producing stack exhaust. The exhaust gases enter the gas turbine (GT) where it expands to a lower pressure and temperature. The thermal energy of exhaust gases is transfer to steam production in the high and low pressure components of NGCC, as such as, superheater (SH), evaporator (EVA), economizer 1 (ECO1) for high pressure and economizer 2 (ECO2) and deaerator (DEA). In the economizer 1, stem portion is extracted to heat the natural gas at 165.9 ºC. The fuel is stored in the liquid state above the critical pressure (46 bar and -84ºC) and should be evaporated and expanded to burn into combustor. The steam extraction to heat the fuel increases the thermal efficiency and avoid the freezing of fuel supply valves. All steam produced in the two gas turbine at point (18) drives the steam turbine. The output of steam turbine is connected to condenser. The water as saturated liquid is shared and enters each dearator of each one gas turbine cycle.

The exhaust gases from post-combustion flow to mitigation system CCS to capture the CO_2. The CCS system decreases the environmental impact due to pollutant removal. According to Peeters et al. (2007) the exhaust gases is cooled and the MEA sorbent absorbs the CO_2 from gases. The scrubbed gases is washed and vented out at point (35). The sorbent is heated by steam from point (37) and return at (38) to reject the CO_2 and regenerated. The CO_2 product exists from CCS in point (36) to be compressed and driven to Geological storage by pipeline. Some fresh MEA is added due to the degradation losses and vapor losses. Some input chemical as MEA is necessary and also generates air emissions with toxic effects during the process. Fig.2 shows a schematic diagram of a flue-gas CO_2 absorption process of CCS system.

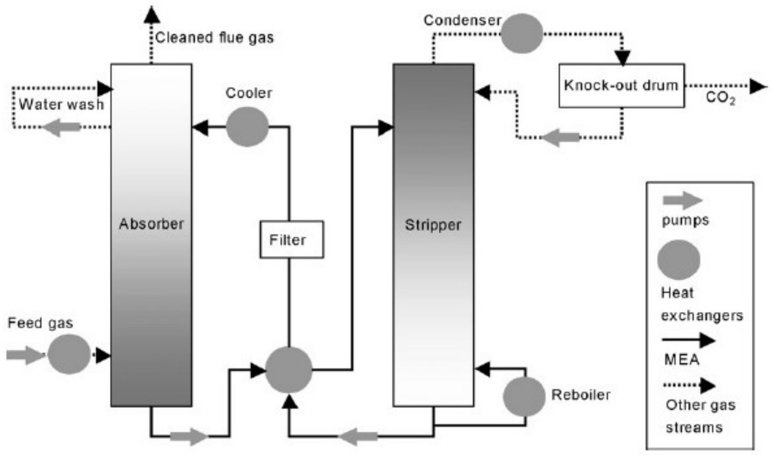

Figure 2 – Schematic diagram of a flue-gas CO_2 absorption process of CCS system. From Peeters et al. (2007)

The CO2 captured is transported into pipeline at 110 bar to avoid two-phase flow. It is compressed by turbine at power plant and transported over 500 km to geological storage. The mass flow rate of CO2 captured is 22.16 x2 =44.32 kg/s or 1.270 Mt/year. According to Singh et al. (2011), additional energy is required for recompression of CO2, due to the pressure drop caused by friction. A pressure drop of 10 bar per 100 km demands a recompression station after 300 km to maintain the pressure above the critical pressure (73.77 bar). The power required for a pressure increase of 30 bar (90 to 120 bar) at CO2 recompression using gas turbine with efficiency of 85% is 275 kW.

3. METHODOLOGY

The exergy, exergoeconomic and exergo-enviromental balances are performed for each component of the power plant. Regarding the exergy analysis, there are several approaches and methods found in literature. To a better understanding of exergy analysis, the total specific exergy is splitted in physical and chemical specific exergy, as following:

$$ex_{ph} = h_i - h_0 - T_o.(s_i - s_0) \text{ [kJ/kg]} \quad (1)$$

$$ex_{ch} = \Sigma(y_i.e_i) + \overline{R}.T_0.\Sigma(y_i.\ln(y_i)) / \Sigma(y_i.M_i) \quad \text{[kJ/kg]} \quad (2)$$

Where T_0 is the environmental temperature [Kelvin], y_i is molar fraction, e_i is the standard molar chemical exergy [kJ/kmol], i is each gas component, $\overline{R}$ is the universal gas constant (8.314 kJ/kmol K) and M is molar mass of gases [kg/kmol].

The Specific Exergy Costing (SPECO) approach was applied in this research. It was described according to Lazzaretto and Tsatsaronis (2006). SPECO works with the definitions of fuel and product. The fuel is defined to be equal to all the exergy values to be considered at the inlet plus all the exergy decreases between inlet and outlet minus all the exergy increases that are not in accord with the purpose of the component. Whereas the product is defined to be equal to the sum of all the exergy values to be considered at the outlet plus all the exergy increases between inlet and outlet that are in accord with the purpose of the component according to The aims of exergy balance are evaluate the exergy destruction and exergetic efficiency for each component. The Exergy balance for each component evaluated the fuel, product and destruction of exergy rate and its exergetic efficiency as:

$$\dot{E}x_f = \dot{E}x_p + \dot{E}x_D \tag{3}$$

$$\varepsilon = \frac{\dot{E}x_p}{\dot{E}x_f} \tag{4}$$

3.1 Exergoeconomic Analysis

This analysis combines both the exergy and the economic analyses to provide the cost of inefficiencies, individual processes or final products of any given system (Bejan et al., 1996). This approach can be useful in several applications, as such as, feasibility studies, for comparing different plants or even in the optimization of thermodynamic systems. The basic thermoeconomic equation applied to all the components is shown as follows:

$$c_p.\dot{E}x_p = c_f.\dot{E}x_f + \dot{Z} \tag{5}$$

Where c_P and c_f represent the average costs per exergy unit of product and fuel, respectively. This equation affirms that the cost rate associated with the product of the system is equal to the sum of the cost rate of fuel and the costs associated to the purchase and maintenance of the component itself.

The capital investment of a component is converted into the cost rate by the following relation according to (Bejan et al., 1996):

$$\dot{Z}_i = \text{f}.Z_i.\varphi/(H.3600) \qquad [\$/s] \tag{6}$$

Where f stands for the annuity factor, Z_i for the cost rate of the component, φ represents the maintenance factor of 1.06 and H is the operation time, which was adopted as 8000 hours per year. The annuity factor is an economical parameter that depends on the interest rate and the estimated equipment lifetime. It is defined through the following equations:

$$\text{f} = \left[\frac{q^{(k+cp)}-1}{(q-1).q^{(k+cp)}} - \frac{q^{cp}-1}{(q-1).q^{cp}}\right]^{-1} \tag{7}$$

$$q = \left(1+\frac{in}{100}\right)\left(1+\frac{ri}{100}\right) \tag{8}$$

In these equations, k represents the plant lifetime, which is adopted as 25 years, cp is the construction period, taken as 3 years, in is the interest rate of 10% and ri stands for the rate of inflation adopted as 8%. The cost of the natural gas is taken as 1.61 \$/kg.

The cost rate of the exergy destruction rate is defined as:

$$\dot{C}_D = c_f.\dot{E}x_D \tag{9}$$

The exergoeconomic factor f_k is calculated as follows:

$$f_k = \frac{\dot{Z}}{c_f.\dot{E}x_D + \dot{Z}} \tag{10}$$

The exergoeconomic factor compares the rate of investment cost ($\dot{Z}$) with the rate of cost of irreversibility ($c_f.\dot{E}_D$). Low values of this factor indicate that the cost of irreversibility is meaningful compared to the cost of investment. The lowest value of exergoeconomic factor indicates that this component has the greatest potential for improvement.

There are dissipative components in which exergy is destroyed without gaining productive purpose (thermodynamically useful). The throttling valve is one example of them. The system has two throttling valves. In cost and environmental impact balance, all costs and environmental impacts associated with owning and operating a dissipative component must be charged directly to the component(s) served by it. The steam throttling valve of heater exchanger of natural gas was charged to the two pump according the entropy variation. The fuel throttling valve of the combustion chamber was charged to the generator. The condenser is also a dissipative component.

In cost and environmental impact dissipated in point 33 were charged in all heater exchanger of heat recover steam generator (HRSG) according the entropy variation of exhausted gases.

In order to evaluate the capital costs of Natural gas combined cycle (NGCC) was included some cost according to Peeters et al. (2007), as such as, instrumentation and Control of 40% of PEC, Piping of 20% of PEC, Electrical material of 11% of PEC, Land of 5% of PEC and Services facilities of 20% of PEC, resulting a value of 96% of PEC (purchase cost) as direct cost (DC). The CCS is not constructed and demands additional infrastructure and chemical [32]. These are 96% as DC plus 37.5% as Indirect cost (IC) plus Start-up costs of 10% of fixed capital investment (FCI). The Indirect cost (IC) is composed by Engineering of 10% of DC, Construction expenses and fee of 10.5% of DC and Contingency of 17% of DC (Abu-Zahra et al., 2007). The fixed capital investment (FCI) is composed by direct cost (DC) plus indirect cost (IC). And, thus the capital costs of CCS is 296.45% of PEC. The total purchase cost of CCS system is according to Abu-Zahra et al. (2009) of $ 28,249,000.

The exergoeconomic and exergo-environmental balances require auxiliary equations based at SPECO approach. They are formulated using the fundamental principles (F and P principles). Table 01 shows the auxiliary equations of the cost balance.

Table 1 – Auxiliary equations in Exergoeconomic Analysis

Component	**Auxiliar equation**	**Principle**
Air compressor	$c_{26}=c_{27}$	Fuel
	$\dot{C}_1 = 0$	Fuel
Gas turbine	$c_3=c_4$	Fuel
Generator	$c_{28}=c_{29}$	Product
SuperHeater	$c_4=c_5$	Fuel
Evaporator	$c_5=c_6$	Fuel
Economizer 1	$c_6=c_7$	Fuel
Economizer 2	$c_7=c_8$	Fuel
Dearator	$c_8=c_9$	Fuel
Steam Turbine	$c_{18}=c_{19}$	Fuel
Condenser	$\dot{C}_{31} = 0$	Fuel
(dissipative	$c_{19}=c_{10}$	Fuel
component)	Cost rate was charged directly to SH, EVA, ECO1, ECO2 and DEA.	-
CEP Condensate extraction Pump	$c_{30} = \dfrac{2.\dot{C}_{29} + \dot{C}_{20}}{2.\dot{E}_{29} + \dot{E}_{20}}$	Fuel
BFP Boiler Feed pump	$c_{31} = \dfrac{2.\dot{C}_{29} + \dot{C}_{20}}{2.\dot{E}_{29} + \dot{E}_{20}}$	Fuel
NG Heater	$\dot{C}_{23} = c_{NG}.\dot{m}_{23}$, c_{NG}=1.61(US$/kg)	Fuel
	$c_{11}=c_{22}$	Fuel
Carbon	$c_{35}^{PH}= c_9^{PH}$	Fuel
Capture	$c_{35}^{CH}= c_9^{PH}$	Fuel
Unit	$c_{36}^{PH}= c_9^{PH}$	Fuel
	$c_{37}=c_{38}$	Fuel
	$c_9= c_9^{PH}$	Fuel
	$c_9= c_9^{CH}$	Fuel
	$c_{35} = \left(c_{35}^{PH}.e_{35}^{PH} + c_{35}^{CH}.e_{35}^{CH}\right) / \left(e_{35}^{PH} + e_{35}^{CH}\right)$	-
	$c_{36} = \left(c_{36}^{PH}.e_{36}^{PH} + c_{36}^{CH}.e_{36}^{CH}\right) / \left(e_{36}^{PH} + e_{36}^{CH}\right)$	-

The exergoenvironmental analysis, the equations are similar, the c and $\dot{C}$ should be changed by b and $\dot{C}$, respectively.

According to SPECO approach (Lazzaretto and Tsatsaronis, 2006), the throttling valve is a dissipative component, which the exergy destruction has no gaining productive purpose (thermodynamically useful). The system has a throttling valve at the combustion chamber. The reduction of cost rate and environmental impact rate at the throttling valve balance was charged to the two pump according to the entropy variation.

3.2 Exergoenvironmental Analysis

The environmental assessment of the plant is performed using the Eco-Indicator 99. This indicator measures the environmental impact in units called point (Pt) or milli-point (mPt). It is outlined through the methodology that the unit of 1 Pt represents one thousandth of the yearly environmental load of one average European inhabitant (Goedkoop et al. 2001). Thus, by its own definition, the absolute value of the impact is not significant, since the main objective is to compare the difference between fuel and products.

The environmental impact rate $\dot{B}$ and the environmental impact per exergy unit are related as follows:

$$\dot{B} = b.\dot{Ex} \tag{12}$$

The environmental impact rate $\dot{B}$ is the environmental impact expressed in Eco-indicator points per time unit (Pts/s or mPts/s). The environmental impact per exergy unit b is the average environmental impact per exergy unit [Pts/GJ or mPts/GJ].

In a similar way to the exergoeconomic balances, the exergoenvironmental balance is performed through the following equations:

$$\dot{B}_p = \dot{B}_f + (\dot{Y} + \dot{B}^{PF}) \tag{13}$$

$$b_P.\dot{Ex}_P = b_F.\dot{E}x_f + (\dot{Y} + \dot{B}^{PF}) \tag{14}$$

In these two equations $\dot{B}_p$ and $\dot{B}_f$ represent the environmental impact rates associated with product and fuel respectively, and b_P and b_F are the corresponding environmental impacts per unit of exergy for product and fuel. The total environmental impact associated with a component $(\dot{Y} + \dot{B}_D)$. The term $\dot{Y}$ the environmental impact related to the component itself including its entire life cycle and is composed by the following terms:

$$\dot{Y} = \dot{Y}^{CO} + \dot{Y}^{OM} + \dot{Y}^{DI} \tag{15}$$

In these expression, $\dot{Y}^{CO}$ is the environmental impact associated with the construction of the component, including its transport, installation and manufacturing, $\dot{Y}^{OM}$ is the impact for the operation and maintenance of the component, while $\dot{Y}^{DI}$ indicates the environmental impact associated with disposal.

The components environmental impacts of each NGCC are evaluated according to methodology of life cycle impact assessment (Goedkoop et al., 2000 and Goedkoop et al., 2001). The LCA phases of components are: (a) Materials-for production processes, (b) Production processes of manufacturing-treatment and processing, (c) Transport processes of materials, components, fuels, (d) Energy demand such as electricity and heat, (e) disposal scenarios. The components environmental impact (EI) is function of its weight. The environmental impact for natural gas production per mass considering the five phases of LCA except for combustion is b=203 (mPt/m^3)/0.725 (kg/m^3) = 280 (mPt/kg) according to software Simapro.

In equations (13) and (14), the term $\dot{B}^{PF}$ represents environmental impact rate associated to pollutant formation and is expressed as:

$$\dot{B}^{PF} = \sum b^{PF} (\dot{m}_{out} - \dot{m}_{in}) \quad (16)$$

These expressions accounts for the all the different pollutant flows that are emitted to the environment. In this work, the pollutant formation is investigated solely at the combustion chamber. The value for the specific environmental impact of CO_2 was taken as 5.45 mPt/kg (Meyer et al., 2009).

The environmental impact related to the exergy destruction of a certain component is calculated as shown:

$$\dot{B}_D = b_F . \dot{E}_D \quad (17)$$

The exergoenvironmental factor is the ratio the contribution of non-exergy related EI to the total EI increase in a component. The first consists of non-exergy related EI and pollutant formation at component. The second consists of the exergy destruction. It should be calculated as following:

$$f_b = \frac{\dot{Y} + \dot{B}^{PF}}{\dot{Y} + \dot{B}^{PF} + \dot{B}_D} = \frac{\dot{Y} + \dot{B}^{PF}}{\dot{Y} + \dot{B}^{PF} + b_F \cdot \dot{E}_D} \quad (18)$$

At pipeline transport, first the CO2 is compressed from 1 bar to 120 bar at power plant and after there is a recompression from 90 bar to 120 bar after 300 km. To reach the same power of Singh et al. (2011) of 275 kW from 90 bar to 120 bar, the CO2 inlet temperature of compressor should be at maximum 41 ºC for mass flow of 36.6 kgs and pressure ratio of 1.33. In this work, the first CO2 compression from 1 bar to 120 is was assumed in a five-stage compressor with intercooling between stages. The inlet CO2 temperature at each stage was 40ºC with gas turbine efficiency of 80% for pressure ratio of 2.6. The gas turbine is drived by an engine with efficiency of 32%, which uses natural gas with lower heat value (LHV) of 47.57 MJ/kg as fuel. The kinetic energy was assumed negligible.

4. RESULTS AND DISCUSSIONS

The exergoeconomic analysis of NGCC is performed according the model described by (Bejan et al. 1996) and the exergoenvironmental analysis is performed according the model described by Meyer et al. (2009) and Cavalcanti (2017).

The data of mass flow rate, temperature, pressure, exergy, cost rate and cost rate per exergy unit, environmental impact rate and environmental impact per exergy unit at each stream are given in Table 2.

Table 02 – Energy, exergy, exergoeconomicc and exergo-enviromental parameters of system.

	$\dot{m}$ [kg/s]	T [°C]	P [kPa]	Ex [kW]	$\dot{C}$ [\$/h]	c [\$/GJ]	$\dot{B}$ [mPt/s]	b [mPt/MJ]
1	402.4	25.0	100.6	0	0	0	0	0
2	402.4	402.6	1325.0	146585.0	35072.0	66.46	1620.0	11.05
3	411.5	1231.0	1259.0	426948.0	92045.0	55.23	4496.0	9.71
4	411.5	621.5	100.6	135147.0	26870.0	55.23	1312.0	9.71
5	411.5	551.7	100.6	112763.0	22420.0	55.23	1095.0	9.71
6	411.5	438.6	100.6	79476.0	15802.0	55.23	771.8	9.71
7	411.5	210.8	100.6	27371.0	5442.0	55.23	265.8	9.71
8	411.5	160.1	100.6	19489.0	3875.0	55.23	189.3	9.71
9	411.5	128.8	100.6	15539.0	3089.0	55.23	150.9	9.71
10	40.5	45.8	10.0	113.2	61.1	149.90	2.9	25.7
11	35.2	30.0	10.0	2.8	3.2	322.80	0.2	55.1
12	75.7	38.7	2137.0	250.9	10189.0	11281.00	482.9	1925.0
13	75.7	82.4	2137.0	1705.0	12234.0	1993.00	575.4	337.5
14	75.7	152.9	513.6	6914.0	15630	628.00	732.3	105.9
15	75.7	155.6	12916.0	8072.0	48094.0	1655.00	2271.0	281.3
16	40.5	305.1	12050.0	15930.0	18512.0	322.80	877.4	55.1
17	40.5	315.6	10641.0	42748.0	27660.0	179.90	1316.0	30.8
18	40.5	575.4	10641.0	62239.0	33578.0	149.90	1599.0	25.7
19	81.1	150.7	20.0	23667.0	12769.0	149.90	608.1	25.7
20				62823.0	55913.0	247.20	2590.0	41.2
21	35.2		12050.0	39749.0	46191.0	322.80	2189.0	55.1
22	3.6	237.6	2635.0	3422.0	3976.0	322.80	188.4	55.1
23	9.1	-84.6	4638.0	473109.0	52917.0	31.07	2556.0	5.4
24	9.1	165.9	3194.0	455509.0	56891.0	34.69	2745.0	6.0
25	9.1	165.9	2711.0	455300.0	56864.0	34.69	2743.0	6.0
26				159295.0	34100.0	59.64	1620.0	10.2
27				153776.0	32918.0	59.64	1564.0	10.2
28				1699.0	373.6	61.08	17.64	10.4
29				149001.0	32765.0	61.08	1547.0	10.4
30				231.7	51.0	61.08	2.4	10.4
31				1476	322.7	61.08	15.2	10.4
32	1256.0	25.0	300.0	251.1			0.0	
33	1256.0	65.0	300.0	13163.0				
34				357426.0	127622.0	99.18	5986.0	16.8
35	389.3	50.0	100.6	4458.0	886.3	55.23	43.3	9.7
36	22.1	130.0	100.6	10309.0	30924.0	833.3	1709.0	165.7
37	31.6	237.6	2635.0	30425.0	35355.0	322.8	1676.0	55.1
38	31.6	110.0	143.2	1357.0				
39				357426.0	141494.0	110.0	5545.0	15.5

In order to evaluate the CCS effect, the results of model are discussed: The steam mass flow rate used in CCS exits from NGCC at point 37 is 31.64 kg/s and returns after the NG heater. To keep constant the thermal energy of exhausted gases, i.e. the temperature at point 9 is kept 128.8 C, the water mass flow rate at Rankine system is increases 8.92% at point 12. Due to that fact, the capacity of Deaerator, economizer 1 and 2, steam turbine, condenser and both pumps are increased and the capacity of evaporator and superheater are reduced. The gas turbine power is the same of 149.0 MW at point 29 and the steam turbine power is reduced in from 102.26 MW to 62.82 MW at point 20. Therefore, the net power of NGCC is reduced from 397.41 MW to 357.43 MW at point 34.

All components of natural gas combined cycle were evaluated. The values of all purchase equipment cost (PEC) of NGCC without CCS and with CCS are 115.70 M$ and 103.12 M$, respectively. Similar to NGCC, all CCS components were evaluated according to Abu-Zahra et al. (2007). They are evaluated based of tonnes of CO2 captured. Its value of all purchase equipment cost is 28.25 M$.

The exergoeconomic analysis reveals that the cost rate per exergy unit of steam turbine increases from 165.0 $/GJ to 247.2 $/GJ at point 20. It happens due to the power reduction of steam turbine from 102.26 MW to 62.82 MW. This comparation is for system without and with CCS. The cost rate per exergy unit of gas turbine is 61.08 $/GJ. Thus, the average cost rate per exergy unit increases from 88.61 to 99.18 $/GJ at point 34. The cost rate at point 34 was composed of the cost rate of electricity without CCS. It is the cost rate of two times gas turbine at point 29 plus the cost rate of steam turbine at point 20 plus the cost rate of two times the exhausted gases at point 9.

The overall specific cost of electricity was evaluated at point 39. The cost rate was composed of the cost rate of electricity. It is the cost rate of two times gas turbine at point 29 plus the cost rate of steam turbine at point 20 plus the cost rate of two times the exhausted gases at point 35 plus the cost rate of CCS plus cost rate of pipeline plus cost rate of storage plus cost rate of inputs plus the cost rate of gas used at compression of CO2. Its value increases from 99.18 $/GJ to **110.0** $/GJ due to the new cost of CCS and infrastructures.

In the exergoenvironmental analysis, the EI rate per exergy unit of steam turbine increases from 27.02 mPt/MJ to 41.23 mPt/MJ at point 20. This fact is due to the same reason of exergoeconomicanalysis, power reduction of steam turbine comparing a system without and with CCS. The EI per exergy unit of gas turbine is 10.38 mPt/MJ at point 29. The average EI rate per exergy unit increases from 14.44 to **16.8** mPt/MJ at point 34. The overall specific EI of electricity at point 39 was composed of average EI rate of electricity due to two gas turbine at point 29 and one steam turbine at point 20 plus the EI rate of the exhausted gases at point 35 plus the EI rate of CCS plus EI rate of pipeline plus EI rate of storage plus EI rate of inputs plus the EI rate of CO2 emission for its compression menus the EI rate of CO2 captured. Its value decreases slightly from 16.8 mPt/MJ to **15.5** $/GJ due to the low power. The EI rate is reduced from 5986 mPt/s to **5545** mPt/s. The reduction of EI due to CO2 captured is proportional the specific environmental impact of CO_2 emission of ($2.\dot{m}_{36}$. 5.45 mPt/kg)= 241.6 mPt/s.

Table 03 shows the specific cost of overall components.

Table 03 – Composition of overall cost rate

Components	**$/h**	**%**	**reference**
NGCC [34]	124,533	94.26	Present work
CCS	5,058	3.83	Abu-Zahra et al. (2007)
Pipeline	2,393	1.81	Singh (2011)
Storage	$9x10^{-6}$	0.00	Singh (2011)
Inputs (MEA, NaOH, activated coal, water, steam)	137	0.10	Singh et al. (2011)
Total [38]	132,121	100.00	

The higher costs of electricity with CCS are in NGCC composed by combined cycle and followed by CCS. The main costs are due to purchase equipment costs.

The CCS energy requirements is for regeneration of solvent, solvents pump, flue gas blower, cooling water pumps and CO2 compression. Its needs other sources as such as water, chemical (MEA, NaOH) and Coal according to Singh et al. (2011). Table 04 shows the inputs cost of CCS.

Table 04 - Components of overall cost rate of CCS

Inputs	(kg/tCO2)	(ton/year)	(mPt/kg)	**reference**	(Pts/year)	%
MEA	1.5	1915	414	Simapro (2018)	792.8×10^3	96.02
NaOH	0.13	166	38	Goedkoop et al., (2000).	6.3×10^3	0.76
Coal	0.075	96	277	Simapro (2018)	26.5×10^3	3.21
Water	800	1.02×10^6	0		0	0.00
Vapor Extracted	1428	1.82×10^6	0		0	0.00
Total	-	-			825.6×10^3	100.00

The values of input mass per tonnes of CO2 were obtained according to Singh et al. (2011). The MEA is make-up due to its loss via vapor. The NaOH is used to reclaim the amine. The active coal is used to remove degradation product. The water is used at CO2 capture process. The CO2 storages is 22.16 kg/s at point 36 operating 8000 h per year. The process captures 1.276 Mt/years (2 x 22.16 x 8000 x 3600). The inputs per year were evaluated multiplying mass per tonnes of CO2 versus 1576. The environmental impact of water is negligible and of vapor is null due to it is produced into the NGCC. The higher enviromental impact of CCS inputs is MEA.

The capture process also generates air emissions due to its loss via vapors and formation of degradation waste. Table 05 shows the emissions and degradation waste.

Table 05 – Environmental impact of emissions and degradation waste generated during CCS operation.

Emissions	(kg/tCO2)	(ton/year)	(mPts/kg)	(Pts/year)	%
MEA	0.063	80.3	3420.0	274.6×10^3	35.15
NH3	0.035	44.6	3420.0	152.5×10^3	19.52
Formaldehyde	0.262	334.1	231.0	77.2×10^3	9.88
Acetaldehyde	0.167	212.9	77.3	16.4×10^3	2.11
Degradation Products	1.680	2144.0	121.6	260.5×10^3	33.34
Total				781.3×10^3	100.00

The values of emissions and degradations products per tonnes of CO2 were obtained according to Singh et al. (2011). The values of emissions and degradation per year were evaluated similar to table 03. The environmental impact of emission per mass of MEA, NH3, formaldehyde, acetaldehyde and degradation products were obtained according to Goedkoop and Spriensma (2001). The emissions composition of degradation products were described at Singh (2011). The higher environmental impact of emissions are at MEA, degradation products, corresponding to 68% of all emissions. It is important to remember that the environmental impact for material production and material emission are different.

The exergo-economic and exergoenvironmental parameters were evaluated. Table 6 shows the exergy destruction rate, exergetic efficiency, average unit cost of fuel and product, the cost rate of exergy destruction rate, cost rate of components, exergoeconomic factor, average unit EI of fuel and product, the EI rate of exergy destruction rate, EI rate of components, exergoenvironmental factor for each component.

Table 06. The thermoeconomic and exergoenvironmental parameters of system

Component	Ex_D [kW]	ε [%]	c_f [$/GJ]	c_P [$/GJ]	C_D [$/h]	Z [$/h]	f [%]	b_F [mPt/MJ]	b_P [mPt/mJ]	B_D [mPt/s]	Y [mPt/h]	f_b [%]
Air Compressor	12,710	92.0	59.5	66.5	2,721	972.4	26.33	10.17	11.05	129.2	31.8	0.00683
Combust. Chamber	138,937	69.5	34.9	50.0	17,352	108.0	0.62	6.03	9.09	837.2	121.2	13.66000
Gas turbine	14,731	95.5	55.2	59.5	2,929	1,844.0	38.63	9.71	10.17	143.0	67.5	0.01310
Generator	3,076	98.0	59.5	61.1	658	194.3	22.79	10.17	10.38	31.3	3.0	0.00264
SuperHeater	2,893	87.1	55.2	84.3	575	106.1	15.57	9.71	14.50	28.1	582.6	0.57280
Evaporator	6,469	80.6	55.2	94.8	1,286	106.9	7.67	9.71	39.05	62.8	29.7	0.01311
Economizer 1	4,498	91.4	55.2	96.9	894	187.2	17.31	9.71	16.72	43.7	38.4	0.02442
Economizer 2	2,673	66.1	55.2	181.1	532	147.2	21.69	9.71	30.13	26.0	8.6	0.00925
Dearator	2,496	36.8	55.2	390.5	496	128.2	20.53	9.71	63.56	24.2	7.2	0.00830
Steam Turbine	37,988	62.3	149.9	247.2	20,494	1,526.0	6.93	25.69	41.23	976.0	325.4	0.00926
CEP	97	58.2	61.1	20,845.0	21	0.2	1.04	10.38	3,557.00	1.0	0.7	0.01977
BFP	309	79.0	61.1	7,784.0	136	0.4	0.30	10.38	1,328.00	3.2	0.8	0.00734
NG Heater	21,018	95.6	33.2	34.7	2,509	0.4	0.01	5.76	6.03	121.1	1.5	0.00034
CCS	8,107	24.2	211.2	1,067.0	6,163	5,058.0	45.07	42.02	181.60	340.6	0.8	0.00007

The higher exergy destruction rate are in the combustion chamber followed by the steam turbine. The exergy destruction at combustor is due to its inherent nature. The steam turbine has low isentropic efficiency. The lower exergetic efficiency are in the CCS flowed by dearator. The CCS requires much steam to operate. The dearator uses steam with high exergy to heat water with low exergy. The higher average unit cost of fuel are in CCS and Steam turbine, which both use steam as fuel. The higher average unit cost of product are in CEP followed by BFP. The high values are due to low increase of exergy rate, which happened in the pumps. The pump output has small increase in exergy rate than at the pump input. The higher cost rate of exergy destruction rate are in steam turbine followed by combustor chamber. Both have the higher exergy destruction rate. The higher component cost rates are in CEP and gas turbine. The lower exergoeconomic factors are in NG heater and BPF. It means that the both components should be invested more money in order to increase its thermodynamic efficiency at exergoeconomic point of view.

At exergo-environmental analysis, the higher average unit EI of fuel are in CCS and Steam turbine, due to the same reason of exergoeconomic analysis. The steam carries all losses and, thus, it has higher EI value. The higher average unit EI of product are in the pumps CEP and BFP. The small increase of exergy rate at pump is the reason this high values. The higher exergy destruction rate related EI rate are in steam turbine followed by combustor chamber due to the higher exergy destruction rate. The higher component EI rates are in SuperHeater followed by steam turbine. These components have higher EI at composition materials and have large material mass.

The lower exergo-environmental factors are in NG heater and BPF. It means that the both components have significant exergy destruction rate related EI rate than to total EI rate. This low value suggests that should be improved the efficiency exergetic in order to increase the environmental performance of entire system. On the other hand, the higher exergo-environmental factor are in combustor chamber followed by super heater. It means that the both components have significant non-exergy related EI than to total EI rate. This high value suggests that should be reduced the component or pollutant formation EI in order to increase the environmental performance of entire system. The combustor chamber has high pollutant formation due to its inherent nature and there is not much to change. However, the super heater should be investigated to reduce its EI at life cycle assessment.

At CO2 pipeline transport for storage, the natural gas consumed was evaluated at two step. First step is the CO2 compression from 1 bar to 120 bar and second step is a recompression from 90 bar to 120 bar after 300 km. The mass flow rate of CO2 is 44.32 kg/s. The compression and recompression consume 1062.5 g/s and 21.8 g/s of natural gas, respectively. The turbine powers are 16,172 and 332 kW, respectively. The CO2 emissions due to natural gas combustion are evaluated according to gas composition, which value of CO2 mass per natural gas mass is 2.661 kg CO2/kg NG. Therefore the CO2 emissions are 2827.3 and 58.1 g CO2/s, respectively. The total CO2 emission for compression and recompression of CO2 is 2.886 kg/s, which flows to geological storage. The environmental impact rate due to the CO2 pipeline transport is 2.886 kg/s x 5.45 mPt/kg = 15.729 mPt/s.

The summary results of power plant performance without and with CCS are shown at table 07.

Table 07 - Effect of CCS on the performance of NGCC

Structure	w/o CCS Value	w CCS	Percentage change
Net power	397.41MW	357.43MW	-10.06%
Exergetic efficiency	43.64%	39.25%	-10.06%
Cost rate of electricity	35.45 US$/s	39.30 US$/s	10.86%
Specific cost	89.2 $/GJ	110.0 US$/GJ	23.32%
EI of electricity	5986 mPt/s	5545 mPt/s	-7.37%
Specific EI	15.1 mPt/MJ	15.5 mPt/MJ	2.65%
CO2 emissions	446 gCO2/kWh	79 gCO2/kWh	-82.29%

The net power was reduced by -10.06% with the CCS. Similar result has been reported by Singh at al. (2011), which reduce the net power from 400 to 340 MW corresponding by -10%. The exergetic efficiency has the same reduction of net power. The fuel exergy is constant. The cost rate of electricity was increased by 10.86% with CCS, due to increase with CCS and infrastructure. The specific cost per exergy was increased by 23.32%, due to reduction of net power. The EI rate of electricity was reduced by -7.37%. The CO2 reduction of 90% is not enough to reduce all emission caused by CCS, its infrastructure and the EI due to production of natural gas. The specific EI per exergy of electricity was increased slightly by 2.65%, due to net power reduction. If the net power was not reduced, the specific EI will be reduced by 7.6 %.

The NGCC emission without CCS of present work is 446 gCO2/KWh. The result of Singh at al. (2011) was 425 g CO2/kWh. The low value of CO2 emissions is due to the higher NGCC thermal efficiency of 55%. The present work has the thermal efficiency of 46%. The CO2 emissions was reduced by -82.29%. The other emissions as MEA, NH3, acetaldehyde, ... were not considered. The work of Singh et al. (2011) which used the Recipe 2008 methodology has reduced the CO2 emission by 75%. This work has used the eco-indicator 99 methodology. Different methodologies should have different weighting at each emissions. And, thus, the comparison should not to be consistent.

CONCLUSION

The aim of this study was to evaluate the EI and cost of electricity from NGCC with CCS. The exergoeconomic and exegoenvironmental methodology were described by Bejan et al.,(1996) and Meyer et al., (2009), respectively. The results reveal that the capture and storage of 90% of CO2 system reduces the CO2 emissions from 446 gCO2/kWh to 79 g CO2/kWh, however multiple emissions appear. Therefore, the global EI of electricity is reduced from 5986 mPt/s to 5545 mPt/s according the eco-indicator 99 methodology. The net power demand is a trade-offs. It is reduced from

397.41 MW to 357.43 MW. The cost rate per exergy unit of product (electricity) increases from 89.2 US$/GJ to 110.0 US$/GJ. And the EI rate per exergy unit of electricity increased slightly from 15.1 mPt/MJ to 15.5 mPt/MJ. The CCS system consumes steam, which is the reason to net power reduction. Further researches as the use of auxiliary system to steam production should be conducted. The solar plant with parabolic trough collector solar is able to produce steam at 400 °C. This combination could increase the environmental performance of CCS system to produce more cleaner electricity.

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