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TECHNICAL ANALYSIS OF BAGASSE GASIFICATION AND COMBINED CYCLE USE IN THE SUGAR INDUSTRY. INCREASE ELECTRICAL SUPPLY.

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Abstract. *Cogeneration is widely applied in the sugar industry, the fuel used (bagasse) is a byproduct of the manufacture of sugar and ethanol process. The steam produced is used to drive steam turbines to produce electricity and mechanical energy and is also used for heating in the production process. However, this type of power generation is below the real potential. One of the ways to improve the process of cogeneration in the sugar industry is the use of biomass gasifiers associated with combined cycle, technology known as BIG-GTCC (biomass integrated gasifier-gas turbine combined cycle). This paper presents a thermodynamic study of the incorporation of BIG-GTCC technology in the sugar industry. A real plant data is referenced, the company has a traditional cycle and the proposed thermodynamic study is performed in two cases. In the first case, air is used as the gasifier agent to produce a synthesis gas with a low calorific value (4 to 6 MJ/kg); in the second case steam/air mixture of 50% each are used, increasing the lower heat value to 10 MJ/kg. The main result is the increase of electricity production of the traditional cycle from 31.23 MW to 67.44 MW for the first case, and to 119.67 MW for the second.*

Keywords: *BIG-GTCC, Energy analysis, bagasse gasification, combined cycle, power generation*

1. INTRODUCTION

Bagasse from sugar cane offers an attractive alternative for obtaining energy, approximately 140 kg of dry bagasse is obtained per ton of crushed cane. If we count on with sugar cane worldwide production of 1661 Mt/year you can get about 11 Mt/year of bagasse, of which 40 % is produced only in Brazil, where the bagasse is a source of biomass available for energy uses. (Pellegrini L. F., Oliveira J. 2011)

A research topic in many countries today is to find the most appropriate technology to enable more efficient use of waste from sugar cane as an energy source. Most authors (Deshmukh E. 2013) agree that the current complex situation requires the sugar industry to undertake major changes that become high efficiency with broad diversification of their production and whose main product is the electricity generation. (Pippo W. A., Garzone P., Cornacchia G. 2007)

In Brazil, much of the research is based in improving the bagasse energy efficiency to increase the electricity supply in the sector. Among the most promising technologies in this area is the BIG-GTCC (Biomass Integrated Gasifier-Gas Turbine Combined Cycle), based on the most modern and efficient cogeneration systems capable of generating energy throughout the year and increase the efficiency energy conversion between (35-40%). (Pellegrini O., Burbano J. 2010), (Pellegrini L. F., Oliveira J. 2011), (Pellegrini et al. 2010), (Moncada J., El-Halwagi M. 2013).

The aim of this paper is to present a comparative theoretical thermodynamic study of cogeneration systems in the sugar industry and alcohol, comparing the current cycle and the incorporation of the BIG-GTCC or combined cycle, considering the impact on yields in the sugar, ethanol, and electricity production.

2. DEVELOPMENT

2.1. Properties of Sugarcane bagasse as fuel.

Bagasse characteristics vary in composition, consistency and calorific value, which will depend on the climate, soil type, variety cane harvest method, cleaning quality cane grinding and the mill grinding efficiency; bagasse is obtained with a humidity of about 50%. This consists of fiber and water soluble materials, mainly sugar and impurities. The fiber composition is similar to other lignocellulosic materials: cellulose (40-50%), hemicellulose (20-30%), lignin (20-25%), ash (1.5-3%). (Moraes et al. 2012), (Pérez M. 2013)

According to its properties, bagasse is classified as a fuel with high reactivity due to its high volatile content and low ash, its calorific value is comparable with that of several woody biomasses. (Jenkins B., Baxter L., Miles T.R. 1998)

2.2. Biomass Gasification

Gasification is a thermochemical process in which biomass is transformed into a fuel gas through a series of reactions that take place at high temperature in the presence of a gasifying agent (air, oxygen, water vapor, CO2 or mixtures of these gases). The generated gas, known as synthesis gas, is mainly composed of H2, CO, CO2, N2, and small particles of coal, ashes, tars and oils. Its lower calorific value (LHV) varies according to the characteristics of biomass and gasifying agent used. In the case of air as a gasifying agent, the LHV is between 4 and 6 MJ/kg, if steam, oxygen or mixtures thereof, it is between 8 and 20 MJ/Nm^3. (Reed A. 1998), (Ruiz J.A., Juárez M.C., Moralesb M.P., Muñozb P., Mendívilb M. A. 2013), (Jarungthammachote S. 2008), (Proenza N., Blanco E., Travieso D., Santana J. Silveira J. S. 2014)

In this study the circulating fluidized bed technology (CFBG) is used, wherein the gasifying agent flows inside the reactor bed at a speed in which the bed material remains in a state of fluidization, achieving an increase in transfer energy between the inert bed material and fuel, and the homogenization of the temperature in the reactor bed. These operate at temperatures of 800-1100 ° C (Fig. 1) (Ruiz J.A., Juárez M. C., Moralesb M. P., Muñozb P., Mendívilb M. A. 2013). Bagasse was used as raw material and air and vapor-air mixture as a gasifying agent. (Proenza N., Blanco E., Travieso D., Santana J. 2014)

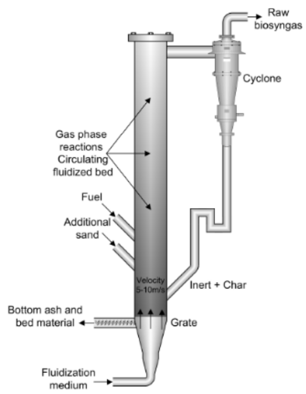

Figura1. Circulating fluidized bed gasifier.

2.3. BIG-GTCC Technology.

The BIG-GTCC technology is advanced and economically competitive with conventional steam turbine technology, used as fuel, the sugar cane bagasse achieves a significant increase in electricity generated per unit of cane processed (Larson E. D., Williams R. H. 2001). In recent years, there have been works that deal with the applicability of these systems in the sugar industry (Walter. A. 1994), (Souza-Santos M. L. 1997), (Arrieta F. R., Silva E. 2000), (Larson E. D., Williams R. H., 2001), (Pellegrini L.F. 2007), (Pellegrini L. F., Júnior S. O. 2010), (Stanek W., Czarnowska L. 2012). Difficulties still to be overcome as the LHV syngas and reliable and efficient systems for cleaning and ensuring the thermal energy required in the production process, however, this technology presents great opportunities to increase power generation in the sugar and alcohol industry.

3. MATERIALS AND METHODS.

Data provided by (Fiomari M. 2004) regarding the sugar and ethanol industry "Pioneiros" located in São Paulo state was used. Fig. 2 shows the plant configuration with its fully electrified drive equipment, the bagasse flow with 50% humidity is 22.53 kg/s and it able to meet the thermal energy demand and produce 31.23 MW of which 24% is consumed by the plant itself. Based on the theoretical analysis, thermodynamic parameters of incorporating the BIG-GTCC is performed in two cases: In case 1, the air is used as the gasifying agent, and in case 2, a mixture of steam/air 50% is used, both with pressurized gasification system.

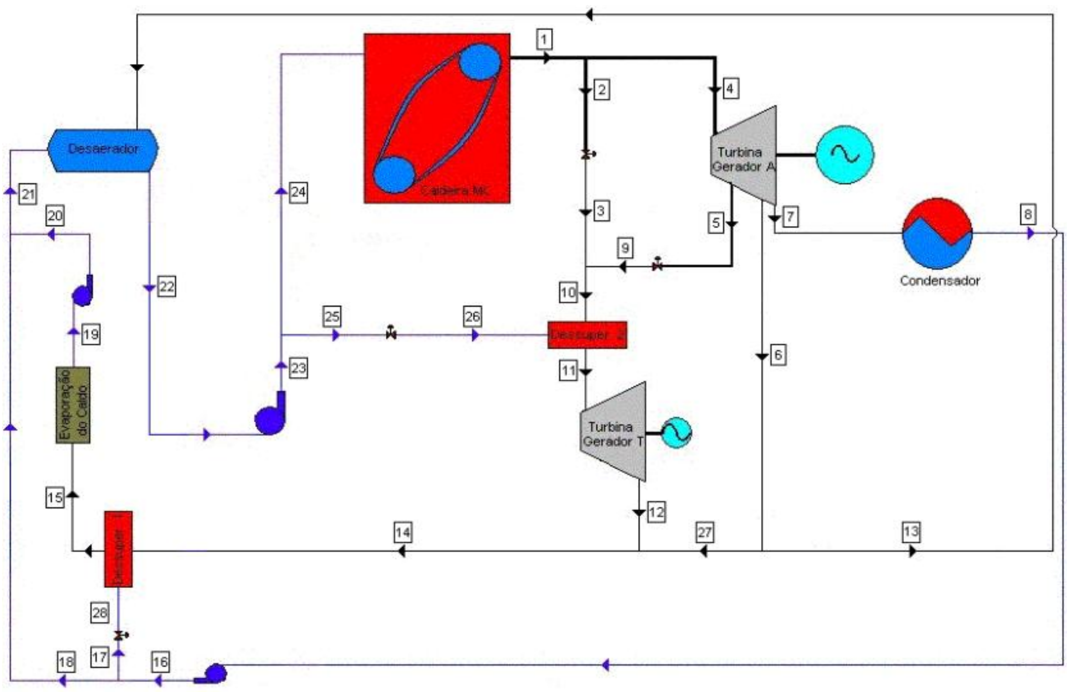

Figura 2."Pioneiros" company flowchart (Fiomari M. 2004)

For case 1, the replacement of boilers burning directly by the BIG-GTCC system is proposed, which includes recovery boiler (HRSG), gas turbine and dryers, roaster, CFBG pressurized system and air as gasification agent (Fig. 3).

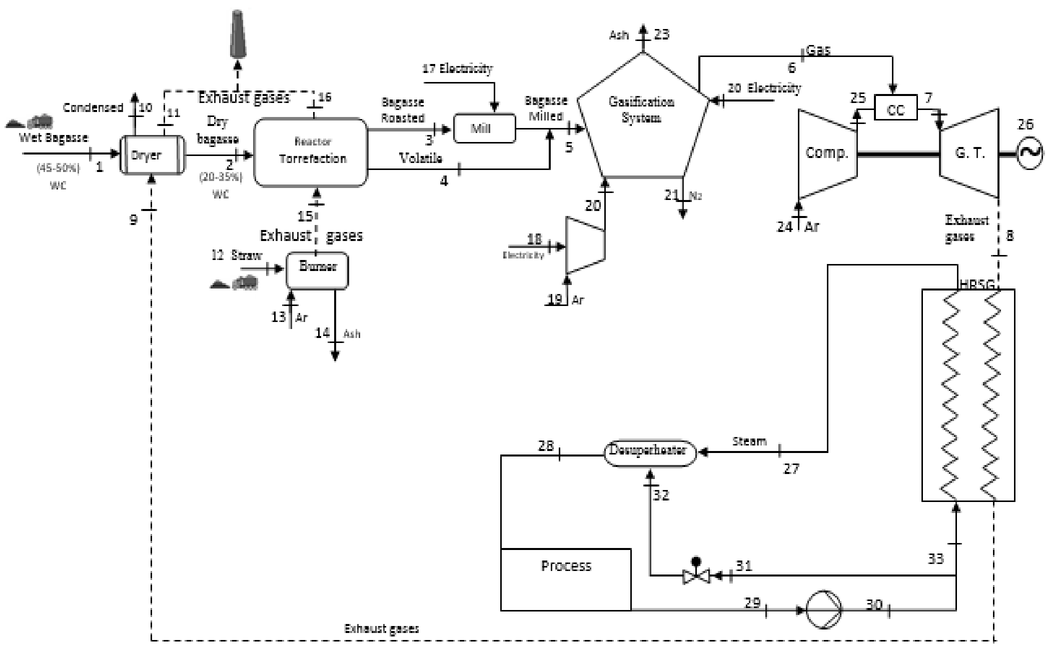

Figure 3. BIG-GTCC technology with CFBG bagasse and air.

In case II the same configuration is kept but using air-steam mixture at 50% as gasifying agent, the steam is extracted at the output of the HRSG, without affecting the process, with the aim of increasing the synthesis gas LHV. The new configuration is shown in Fig. 4.

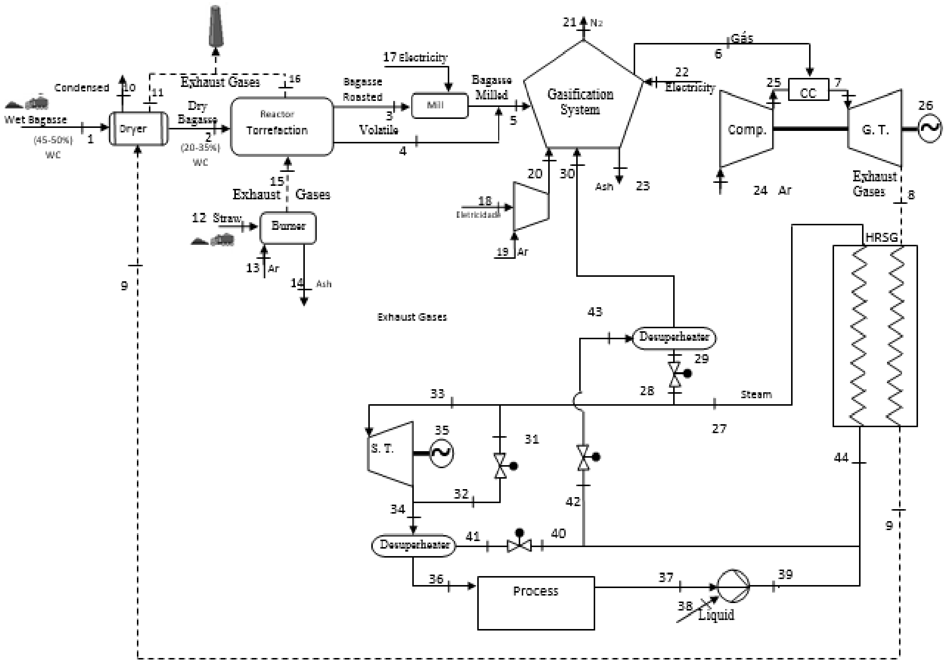

Figure 4. BIG-CC technology with CFBG bagasse and air/steam.

For the plant analysis the following parameters given in the chart were considering:

Table 1. Plant default data (Fiomari M. 2004)

Data	Values	Data	Values
η_{Dryer} (%)	60	ΔP_{CC}	0.05
η_{roaste} (%)	60	ΔP_{CR}	0.05
$H_{HRSG.}$ (%)	70	h_o(kJ/kg)	104.86
$\eta_{comp.}$ (%)	83	LHV $_{bag.dry}$ (kJ/Kg)	15000
η_{tgiso} (%)	89	LHV $_{bag.wet}$ (kJ/Kg)	7320
η_{CC} (%)	90	$LHV_{gas.ar}$ (kJ/Kg)	6000
η_e (%)	95	T_o(°C)	25
$T_{s. GT}$ (°C)	500-700	$T_{S. HRSG}$ °C	150-250

Where:
η: Working efficiency of each equipment
ΔP: Pressure variation
h: Enthalpy
T: Temperature

The gas turbine selection is performed according to the method proposed by (Antunes J. S. 1999) and using the available equipment on the market (WORLD GAS. 2012) considering the compliance needs of thermal energy and power to guarantee the production process.

The gas turbine exhaust gases mass flow is calculated by Eq. (1).

$$\dot{m}_{Gas} = \frac{\dot{m}_{steam}.(h_{out} - h_{in})}{\eta_{cr}.Cp_g.(T_{in.\ mean} - T_{initial})} \quad (1)$$

Where:
$\dot{m}_{Steam}$: Steam mass flow in the HRSG (kg/s)
$T_{in.\ mean}$: Gas temperature at the exit of the HRSG (°C).
$T_{initial}$: Gas temperature to the input of the HRSG (°C).

h_{out}: enthalpy outlet steam in the HRSG (kJ/kg)
h_{in}: Liquid enthalpy input to the HRSG (kJ/kg)
η_{cr}: Efficiency of the HRSG (%)
Cp_{gas} = 1.23 kJ/kg. K (Krasnoschiokov E. A. 1977)

It should be considered a pinch point (ΔT) in the HRSG. The minimum temperature variation for the cooling profile of the gases from the turbine ΔTp has a value between 10°C and 30 °C (Marsh K. 1987), 20 °C is adopted. The temperature at the dew point is determined using Eq. (2) and to calculate the temperature of the exhaust gases is used Eq. (3): (Villela, C.; Silveira J. L. 2007)

$$T_{dew} = T_{Saturation} + \Delta T_p \tag{2}$$

$$T_{outHRSG} = T_{outGT} - \left(\left[\frac{T_{outGT} - T_{dew}}{H_R - H_C} \right] . H_R \right) \tag{3}$$

The rates of heat transferred (HC) and received (HR) are given by the following equations:

$$H_R = \dot{m}_{Steam} \, .h_l \tag{4}$$

$$H_C = \dot{m}_{gas} \, .Cp_g \, (T_{gas}) \tag{5}$$

Where, h_l is the specific enthalpy of saturated liquid at HRSG entrance.

Altitude, room temperature, and relative humidity were also considered as they affect the performance. It was considered an altitude of 760 m, temperature of 25 °C and relative humidity of 60%.

The HRSG has a pressure loss of 5% according (Antunes J. S. 1999). Knowing that the gases are expelled at the 101.3 kPa atmospheric pressure, can be calculated the gas turbine exhaust gases pressure and the pressure ratio using the following equations:

$$P_{out\ GT} = \frac{P_{outHRSG}}{1 - \Delta P_{HRSG}} \tag{6}$$

$$r_p = \frac{P_{int\ GT}}{P_{out\ GT}} \tag{7}$$

To determine the temperature of inlet gas to the gas turbine is used Eq. (8). According to (Villela, C.; Silveira J. L. 2007), the isentropic efficiency of the gas turbine adopted is 89% and the specific heat ratio *(k_g)* is 1.33

$$T_{int\ GT} = \frac{T_{outGT}}{\left(1 - \eta_{tgiso} \cdot \left[1 - \left(\frac{P_{int\ GT}}{P_{outGT}} \right)^{\frac{1-K_g}{K_g}} \right] \right)} \tag{8}$$

According with (Antunes J. S. 1999), the combustion chamber (CC) pressure loss is 5%, based on which the compressor outlet pressure is calculated by Eq. (9).

$$P_{int\ CC} = \frac{P_{int\ GT}}{1 - \Delta P_{cc}} \tag{9}$$

The isentropic compressor efficiency adopted is 80% and the ratio of specific heats (k_{ar}) is 1.4 (Villela, C.; Silveira J. L. 2007). The temperature and pressure in the compressor inlet were considered environmental. From these values the inlet temperature can be calculated to the CC by Eq. (11) (Antunes J. S. 1999).

$$T_{int\ CC} = T_{outComp} \cdot \left(1 + \frac{1}{\eta_{cpiso}} \cdot \left[\left(\frac{P_{int\ CC}}{P_{outComp}} \right)^{\frac{K_{ar}-1}{K_{ar}}} - 1 \right] \right) \tag{10}$$

For the calculation of the electrical power generated (E_{tge}), Eq. (11) can be used, considering the electricity generator efficiency of 95% generated by the fuel (E_{fuel}) is calculated through Eq. (12), considering the efficiency of the gas turbine is 35%.

$$E_{tge} = E_{tg} * \eta_e \tag{11}$$

$$E_{fuel} = \frac{E_{tge}}{\eta_{tg}} \tag{12}$$

The mass flow of syngas ($\dot{m}_{gas}$) is calculated using Eq. (13). The LHV of the syngas is approximately 6 MJ/kg for case I (air) and 8 MJ/kg for case II (air-steam mixture). (Pellegrini L. 2010)

$$\dot{m}_{gas} = \frac{Efuel}{PCI_g} \tag{13}$$

The mass flow of dry bagasse is calculated by Eq. (14), according to (Reed T. B. 1998; Larson, E. D. 2001; E. 2009; Worley M., Yale J. 2012), cold efficiency pressurized gasification system is 80% and the bagasse LHV dry basis is 15 MJ/Kg. (Miles, T. R. 1995). For the mass flow of wet bagasse, with 50% humidity, that meets the parameters of the cogeneration system and the process, Eq. (15) is used. The LHV is 7.32 MJ/kg.

$$\dot{m}_{bag.dry.} = \frac{E_{fuel}}{\eta_{gase}.PCI_{beg.dry}} \tag{14}$$

$$\dot{m}_{bag.Wet} = \frac{\dot{m}_2.PCI_{bag.dry}}{PCI_{bag.wet}} \tag{15}$$

To find the overall electrical efficiency (η_{ge}) and (η_{gl}) of the plant Eqs. (16) and (17) are used considering the plant energy consumed and the BIG-GTCC system.

$$\eta_{ge} = \frac{E_{tge} + E_{tve} - W_b}{E_{comb}} \tag{16}$$

$$\eta_{gl} = \frac{\sum E_{elec.} + \sum Q_{proc} - \sum E_{cons.}}{E_{fuel}} \tag{17}$$

According to (Machin E. 2015), the required energy for drying and roasting bagasse is 0.678 MJ / kg to 1.75 MJ / kg respectively. This energy demand is covered in the case of drying with the exhaust gas HRSG decreasing the moisture to 20%. The energy required for roasting is obtained from the burning of 3.44 kg/s of straw, a burner is added, the straw features are similar to the wet bagasse and its LHV is 7.32 MJ/kg.

4. RESULTS ANALYSIS

Based on the methodology described above the gas turbines that meet the technical parameters of the plant were selected, they are shown in Tab. 2.

Table 2. Gas turbines selected for case I and II. (WORLD GAS. 2012)

Case	I	II
Manufacturer	SIEMENS ENERGY [60Hz]	SIEMENS ENERGY [60Hz]
Model	SGT6-5000F	SGT6-5000F
Electric Power Ep [kW]	67443	111439
Heat Rate [Btu/kWh]	8808.1	9181.6
Efficiency [%]	35	35
Pressure Ratio [r_p]	15.7	12.9
Rotation [rpm]	3600	3600
$T_{exhaust}$ [ºC]	597	544
Mass flow of exhaust gas ($\dot{m}_{out}$) [kg/s]	217.5	425.2

The difference between the turbines of case I and II are directly related to the fuel energy produced. By using air-steam mixture, increases the syngas LHV which results in an increase of the plant power generation.

The electricity production increased in both cases compared to the traditional cycle, in case I production reaches 67.4 MW of which 36 % is consumed in the technological process of the plant, with 42.5 MW for sale purposes. In case II electricity production reaches 119.7 MW of which the company consumes 16.9 %, with a surplus of 99.5 MW for sale purposes (Fig. 5). This increase is achieved without the need of an external source of bagasse to be gasified.

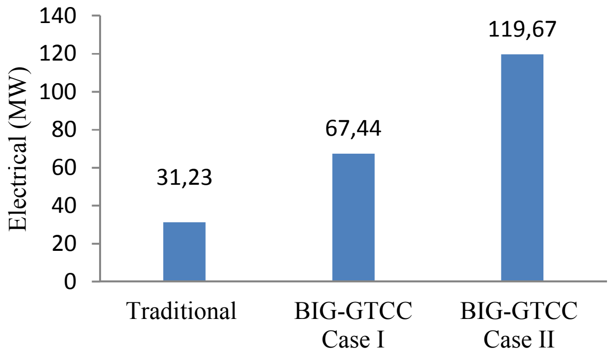

Fig. 5. Electric power produced.

The electrical efficiency in both cases increased compared with the traditional plant, in case I up to 27% and the second to 60.3%, the difference is because there was no electricity generation from steam in case I, and in case II it does. The overall plant efficiency for the case I shows a significant reduction over conventional because no electrical power is produced with the steam turbine, for case II increases the overall efficiency compared to the traditional 16% by employing steam turbine which justifies the increase.

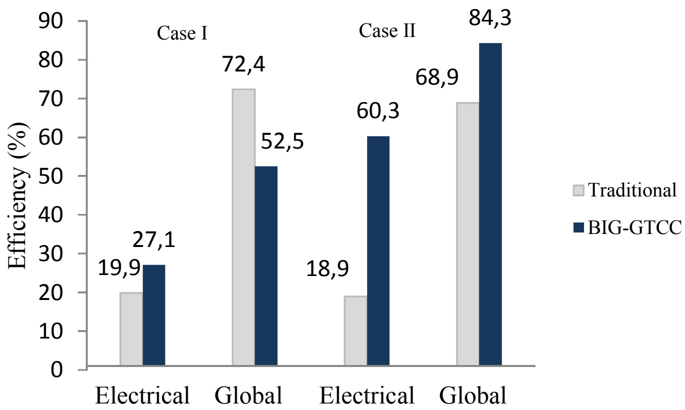

Fig. 5. Electric and global efficiency.

5. CONCLUSIONS

A study of the thermodynamic parameters of the incorporation of the BIG-GTCC technology in the sugar industry and alcohol was presented, with reference to the distillery "Pioneiros" to increase power generation, using air for gasification, in case I, and vapor-air mixture of 50 % in case II. The electricity generation increased from the traditional plant, although the best results is shown in case II achieving a power generation of 119.7 MW without purchasing additional bagasse.

The power generation efficiency in the traditional plant is 19.9 % and increases in case I to 27.1 % and 60.3 % in case II, the difference in efficiency is given by the possibility of electricity generation in the steam turbine in case II, which is not possible in the case I.

Studying the plant overall performance, in the traditional cycle is 72.4 %, while in the case I decreases to 60.3 % and in case II reaches a better performance of 84.3 %, which is related to the production electricity from steam.

It is concluded that the BIG-GTCC technology presents greats opportunities to increase power generation in the sugar industry.

Analysis is recommended from the economical and environmental point of view of the incorporation of technology in the sugar industry.

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