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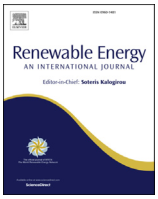

Technical assessment of the Biomass Integrated Gasification/Gas Turbine Combined Cycle (BIG/GTCC) incorporation in the sugarcane industry

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ABSTRACT

Biomass Integrated Gasifier/Gas Turbine Combined Cycle (BIG/GTCC) systems in the sugarcane industry, are capable to produce more electricity per unit of biomass consumed than the conventional Condensing Extraction Steam Turbine (CEST) systems. A technical analysis of the introduction of BIG/GTCC technology in the sugarcane industry for electricity and heat generation, using wet sugarcane bagasse as fuel, was conducted. For sugar plants, with large steam requirements, the implementation of the "pure" BIG/GTCC is not convenient due to the size of the required gas turbine and of the gasification island. The "partial" BIG/GTCC appear to be better alternative, by the combination of the torrefaction pretreatment and entrained flow gasifier, CHOREN Carbo-V® type, permitting a net electricity generation efficiency of 14.7% and the increment of the CEST cogeneration efficiency; , using wet sugarcane bagasse as feedstock. This arrangement avoid observed problems in previous experiences with the continuum handling and feeding of shredded sugarcane bagasse to the gasifier.

1. Introduction

Sugar cane is cultivated in more than 80 countries and the byproducts obtained from the sugar production process represent a great biomass potential. The harvest of sugarcane in the producing countries is about 1.2 Gt and potentially its residue can be used for an electric power production of about 300 TWh y^{-1} [1]. Sugar cane has a great capacity to produce biomass, yielding about 100 t ha^{-1}.

Traditionally, sugar mills use bagasse with high moisture content and cane trash as fuel for low-pressure boilers to generate steam for power generation using a conventional condensing-extraction steam-turbine (CEST) technology, to provide the plant of heat, electricity and mechanical power.

The Biomass Integrated-Gasifier/Gas Turbine Combined Cycle (BIG/GTCC) technology, has being identified by several authors [2–5] as an advanced technology; with the potential to be cost-competitive with CEST in the sugar industry; increasing the electricity generated per unit of sugarcane processed.

Larson et al. [2] reviews the BIG/GTCC designs and commercial projects and presented estimates of the performance of two different BIG/GTCC plant configurations integrated into sugar mills (total and partial integration). In the study were not considered unsolved the problems observed during the continue feed of gasifier with sugarcane bagasse. The gasifier types considered was fluidized-bed reactors.

On this background, the objective of this work is to perform a study of the introduction viability of the BIG/GTCC technology in the sugar industry in order to increase the electricity generation from renewable energy sources of energy, in a sustainably way. The study will analyzes two possible configurations for the incorporation of this technology, considering the use of an advanced gasification technology (entrained flow) and the inclusion of torrefaction pretreatment technology to overcome the feeding problems observed when sugarcane bagasse is feed continuously to a gasifier [1,2].

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Nomenclature

$\dot{m}_x$	Mass flux of element x [kg/s]
Δh_x	Enthalpy change of the element x [MJ/kg]
h_{fg}	Water vaporization enthalpy [MJ/kg]
Q_T	Heat lost in the torrefaction reactor [MW]
E_{comb}	Energy supplied by the sugarcane bagasse [MW]
E_{tge}	Electricity generate by the gas turbine [MW]
E_{tve}	Electricity generate by the steam turbine [MW]
Q_G	Heat lost in the gasifier reactor [MW]
Q_{Proc}	Thermal energy of consumed by the sugar production process [kW]
Q_{eg}	Thermal energy of exhaust gases [kW]
Q_s	Heat lost in the dryer [MW]
W_{CASU}	Energy consumed by the Cryogenic Air Separation Unit [MW]
W_{LHV}	Energy consumed by the producer gas compressor [MW]
W_{Mec}	Mechanical energy consumed by the sugar production process
W_{Mill}	Energy consumed by the torrefied bagasse mill [MW]
W_b	Energy consumed by the HRSG pump [MW]
η_{GE}	Electricity generation efficiency [%]
η_{GL}	Global efficiency [%]
η_e	Efficiency of gas turbine electricity generator [%]
$\eta_{gasifier}$	Reactor cold gas efficiency [%]
η_{tgiso}	Isentropic efficiency of the compressor [%]
BFBG	Bubbling Fluidized Bed Gasifier
EFG	Entrained Flow Gasifier
HRSG	Heat Recovery Steam Generator
HHW_x	Higher heating value of element x [MJ/kg]
LHW_x	Lower heating value of element x [MJ/kg]
Cp	Specific heat at constant pressure [1/kg K]

Subscripts

bgTorref	Torrefied sugarcane bagasse
CC	Combustion chamber
GE	Exhaust gases
GEC	Exhaust gases of bagasse combustor
GET	Exhaust gases of HRSG
Pgas	producer gas)
dbg	Dried bagasse
wbg	Wet bagasse

2. The conventional condensing-extraction steam-turbine technology

A conventional condensing-extraction steam-turbine (CEST) technology is traditionally used by the sugarcane industry using bagasse as fuel to generate the plants' energy requirements. In a simple Rankine cycle (Fig. 1), high pressure superheated steam is used as the working fluid, generated from saturated liquid water (feed-water). This saturated steam flows through the turbine, where its internal energy is converted into mechanical work to run an electricity generation system. Not all the energy from steam can be utilized for running the generating system because of losses due to friction, viscosity, bend-on-blade etc. and most of the heat energy is rejected in the steam condenser. The feed water brings the condensed water back to the steam generator.

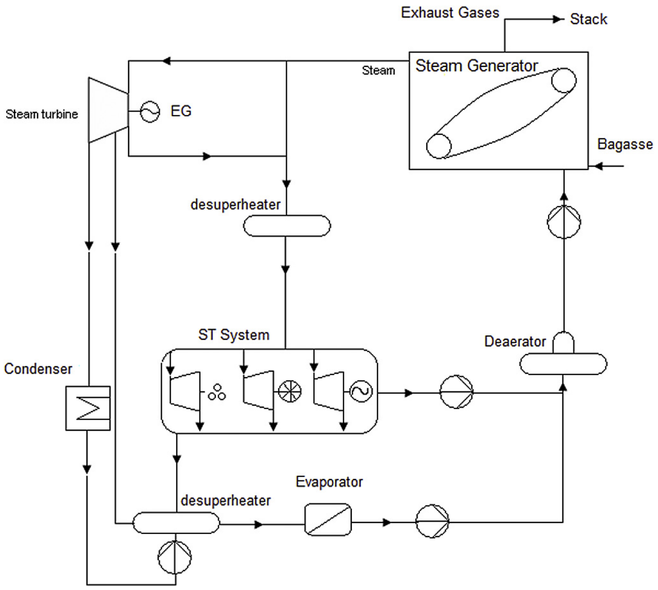

Fig. 1. CEST configuration.

In recent years more modern systems for burning bagasse in suspension have been introduced, that allow to raise the steam pressure and temperature for the purpose of obtaining a higher electric power cycle cogeneration [6]. According to Barroso et al. [7], the typical overall efficiency of this process is in the 15–30% range, consequently the size of conventional combined heat and power generation plants from bagasse, have been limited by these low efficiencies and the amount of fuel within an economical transportation radius.

3. Biomass gasification

Gasification is the key technology of biomass based power generation. Is a high-temperature process (873–1273 K) that decomposes complex biomass hydrocarbons into gaseous molecules, primarily hydrogen, carbon monoxide, and carbon dioxide; also are formed some tars (PAH- polycyclic aromatic hydrocarbon), char, methane, water, and other constituents [8–11]. Hydrogen and carbon monoxide are the desired product gases, because they can fed directly gas turbines for power generation or used in chemical synthesis. The main reactions of biomass gasification are as follows:

$$C + H_2O \rightarrow CO + H_2 \quad \Delta H^0_{298} = 131.5\ \text{kJ mol}^{-1} \tag{1}$$

$$C + CO_2 \rightarrow 2CO \quad \Delta H^0_{298} = 172\ \text{kJ mol}^{-1} \tag{2}$$

$$CO + H_2O \rightarrow CO_2 + H_2 \quad \Delta H^0_{298} = 41\ \text{kJ mol}^{-1} \tag{3}$$

$$CH_4 + H_2O \rightarrow CO + 3H_2 \quad \Delta H^0_{298} = 206\ \text{kJ mol}^{-1} \tag{4}$$

The extent of the above reactions, the products distribution and the producer gas composition is a function of gasification conditions, such as gasification temperature, oxidant/biomass ratio, biomass composition and the residence time of the biomass particle in the reactor.

4. Biomass Integrated Gasification/Gas Turbine Combined Cycle (BIG/GTCC) in the sugar industry

A primary advantage of biomass gasification over biomass direct combustion for electricity generation applications is that the power generation efficiency of a gas turbine combined cycle system is higher than the efficiency of biomass combustion processes that uses a steam cycle alone. Other advantage of the gasifying process is that a difficult solid fuel, like wood and wood residuals, is converted into a readily handled and easily burned fuel gas.

The principal requirement that hinders the implementation of this technology in sugar mills, is that the water content of feedstock should be in the 10–20% range in order to realize cold gas efficiencies above 70% [12]. This requirement makes the feedstock preparation one of the major problems that prevent its large-scale application in the sugar industry, considering that the sugarcane bagasse has a high humidity content when produced in the mill. Therefore, it is imperative to carry out a pre-treatment process to upgrade these biomass characteristics, in order to use this biomass as fuel for fluidized bed or entrained bed gasification, requiring additional energy consumption [13].

Some researches has shown the potential of Biomass Integrated Gasification Gas Turbine Combined Cycle (BIG/GTCC) based systems to be competitive with, if not superior to, conventional combustion power plants because of their higher efficiency, superior environmental performance, and competitive cost [14–16]. However much of the advancements are still under research and development.

BIG/GTCC is a combination of two leading technologies: the gasification, and the gas turbine combined cycle. The gasification stage of the BIG/GTCC plant produces a gas that feed gas turbine.

Typical operating temperature of a fluidized bed is 1073–1123 K, using air as gasification agent. Air is blown through the bed at a sufficient velocity to keep the bed materials in a state of suspension. The fuel particles introduced to the reactor, are mixed very quickly with the bed material and almost instantaneously are heated up to the bed temperature and gasified.

In an entrained flow gasifier, the fuel is be injected together with oxygen, mixtures of steam and oxygen or air. There is a zone where most of the molten slag is collected. The products leaving the reactor at high temperatures and the fuel gas require a cooling process prior to cleaning.

After the producer gas leaves the gasifier, it goes through a cleaning unit where is cleaned of solids, tars, and other contaminants, sufficiently for the gas turbine requirements. After the cleaner unit, the gas is led to a boost compressor that compresses it to the pressure conditions of the gas turbine combustion chamber.

The exhaust heat from the gas turbine is recovered in the Heat Recovery Steam Generator (HRSG) in order to produce steam. This steam then passes through turbine to power another generator, which produces more electricity and the steam from the turbine extraction is used to satisfy the process requirements.

4.1. *Methodology for the technical analysis*

The technical analysis of the implementation of the BIG-GTCC in the sugar industry in Brazil, consider, as the baseline of the study, the configuration of a conventional sugar mill. The study evaluated the implementation of three different configurations, that ensuring demand for steam of the cogeneration plant.

In all cases, are determined the generation efficiencies of electricity, process heat, mechanical energy; and the overall efficiency.

In the final stage, was performed a comparison taking into account the thermodynamic efficiency of different cases and the technical possibilities of the implementation of each one to determine the best, from the technical point of view was performed. Fig. 2 shows the technical analysis methodology for incorporation of BIG-GTCC in the sugar mill.

The incorporation of sugarcane bagasse gasification in the sugar industry could be partial or pure. The “partial” implementation, keeps the existing cogeneration system at the plant and only is gasified the surplus bagasse of the process. In the case of “pure” implementation, the BIG-GTCC system replaces the conventional cogeneration system CEST. It is necessary, that after the incorporation of BIG-GTCC system on partial or pure way, the steam generation of the cogeneration plant, ensure thermal requirements of the process.

4.2. *Implementation of the “pure” BIG/GTCC system in the sugarcane industry*

The sugarcane baseline, where will be implemented the BIG/GTCC technology, have a processing capacity of 276.9 t h^{-1} of sugarcane in the harvesting season. This plant produces 78.9 t h^{-1} of sugarcane bagasse with humidity content between 45 and 50% wet basis, of which 70.5 t h^{-1} are combusted in a boiler, designed to generate nominally 150 t h^{-1} of steam at a pressure of 6468 kPa and temperature of 803 K. The plant has a turbo generator that is capable of generates up to 40 MVA of electricity nominally with a multistage extraction-condensing steam turbine, that produces 19.12 MW. The thermal and mechanical energy consumed in the sugar production process are 88.707 MW and 3.919 MW respectively.

The feedstock (bagasse) is composed of fiber and water-soluble materials, mainly sugar and impurities. The fiber composition has an average composition of 50% cellulose, 25% hemicellulose and 25% lignin [17]. Table 1 shows the main properties of sugar cane bagasse reported by several authors).

The bagasse is classified as a fuel with high reactivity due to its high content of volatiles and low ash content, making of this biomass, a good feedstock for gasification.

For the implementation of the “pure” BIG/GTCC cycle in this sugar mill, the steam produced in the HRSG from the heat of the exhaust gases of the gas turbine must satisfy the high-pressure steam requirements for the process; was considered that the energy consumed by the pumps associated to the HRSG are equal to the consumed in the conventional configuration, i.e. 0.605 MW (see Table 2).

4.2.1. *Case 1. Gasification of bagasse in bubbling fluidized bed and replacement the conventional boiler by BIG-GTCC system (BIG-GTCC “pure”)*

In this case, is analyzed the gasification of the sugarcane bagasse in bubbling fluidized bed gasifier and the replacement of the boiler in the conventional configuration by the gasifier-gas turbine-HRSG system, (BIG-GTCC “pure”), using drying process as pretreatment of the wet bagasse. Fig. 3 shows a scheme of the implementation of a “pure” BIG/GTCC system in the baseline sugar industry.

The energetic analysis was based in the First Law of Thermodynamics considering the process in steady state. Was also considered, based in the mean composition of sugarcane bagasse shows in Table 1 that the air stoichiometric ratio (kg air/kg sugarcane bagasse) was 4.36.

Fig. 4 shows the mass and energy balances on sugarcane bagasse dryer according to the experimental results reported by Prins et al. [27].

Equations (5) and (6) present the dryer energy balance on sugarcane bagasse dryer according to the control volume shows in Fig. 5:

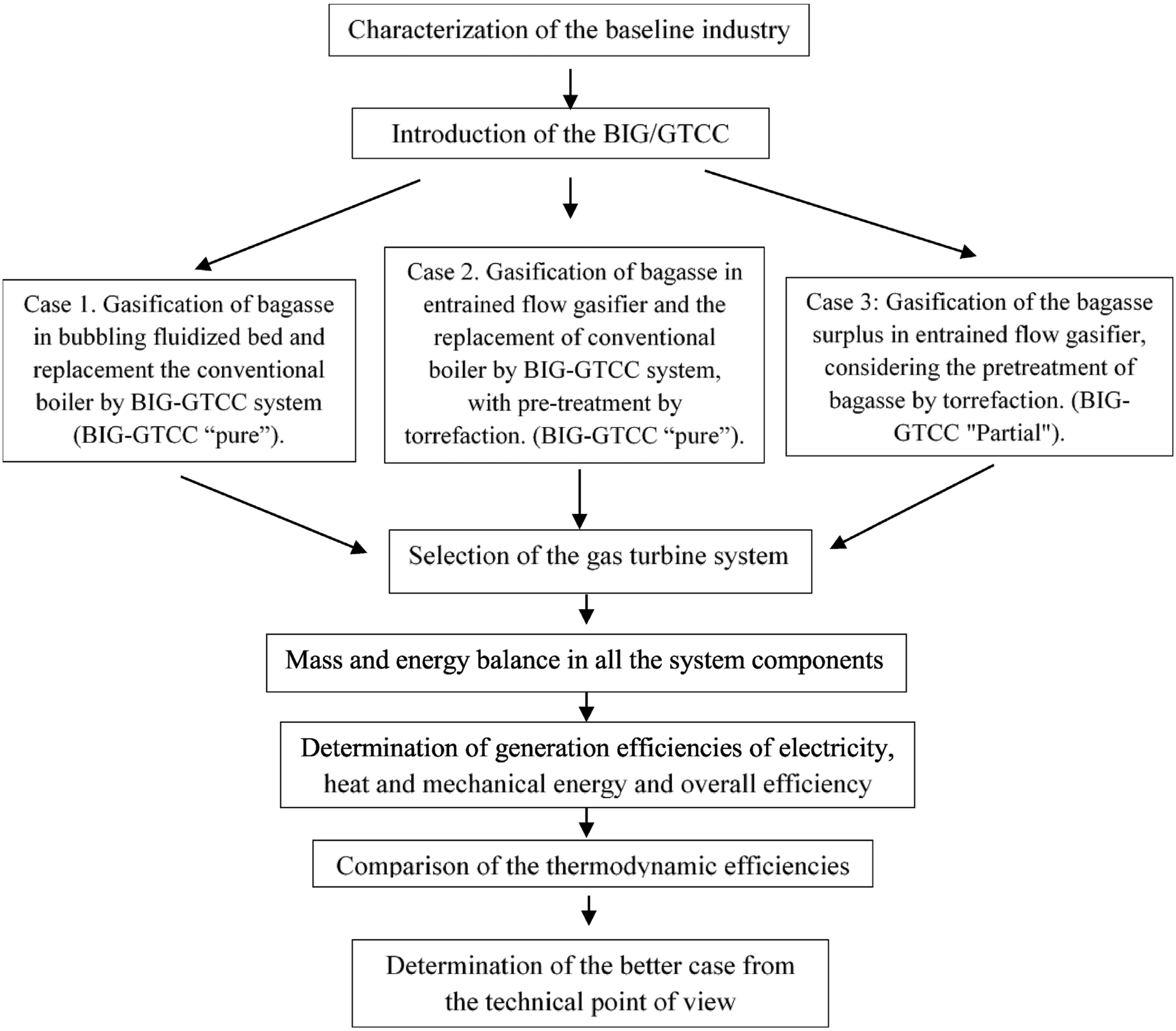

Fig. 2. Technical analysis methodology for incorporation of BIG-GTCC in the sugar mill.

Table 1
Main physical and chemical properties of sugar cane bagasse.

	Ref [18]	Ref [19]	Ref [20]	Ref [21]	Ref [22]	Ref [23]	Ref [24]	Ref [25]	Ref [26]
Proximate analysis									
Volatile matter (wt.%, dry basis)	87.06	83.0	85.61	83.0	88.7	82.1	85.43	79.35	n.a
Fixed carbon (wt.%, dry basis)	12.94	13.0	11.95	13.0	9.3	16.3	12.89	17.88	n.a
Ash (wt.%, dry basis)	n.a.	4.0	2.44	1.9	2.0	1.6	1.68	3.66	6.8
Higher heating value (MJ. kg^{-1}, dry basis)	18.6	18.9	18.99	n.a	18.7	19.19	19.14	19.41	18.85
***Ultimate analysis* (wt.%, dry basis)**									
C	47.0	46.3	48.65	45.48	42.9	48.81	49.0	48.4	46.7
H	5.9	6.4	5.87	5.70	5.9	6	5.87	6.01	6.2
O (by difference)	45.81	43.0	42.82	45.21	49.0	43.1	43.27	41.61	39.8
N	0.33	n.a.	0.16	0.40	0.20	0.46	0.1	0.17	0.2
S	0.05	0.1	0.04	0.06	n.a.	0.1	0.06	0.02	0.02
Cl	n.a.	n.a	0.03	n.a.	n.a	<0.01	0.02	n.a	0.06

Table 2
Considerations for the energetic analyze.

Parameters	Values	Units
η_{HRSG}	70	%
R_g	0.29	kJ/kg.k
$\eta_{compressor}$	80	%
η_{tgiso}	89	%
η_{CC}	95	%
ΔP_{CC}	0.05	kPa
ΔP_{HRSG}	0.05	kPa
η_e	95	%

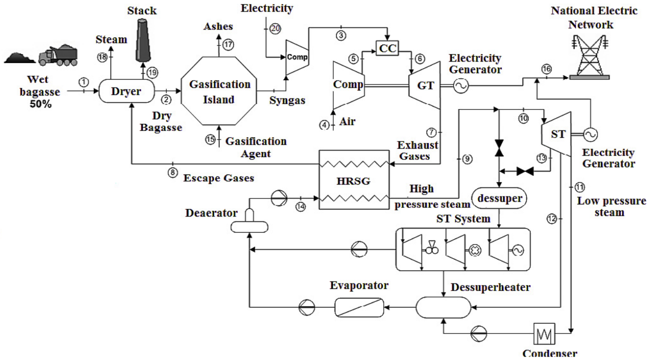

Fig. 3. Simplified scheme of a biomass integrated-gasification/gas turbine combined cycle (BIG/GTCC) system. (BIG-GTCC “pure”).

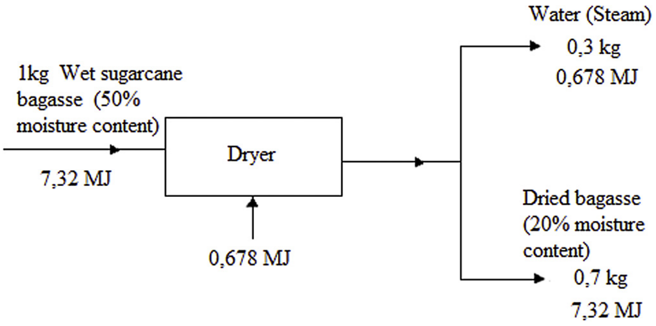

Fig. 4. Mass and energy balances on sugarcane bagasse dryer.

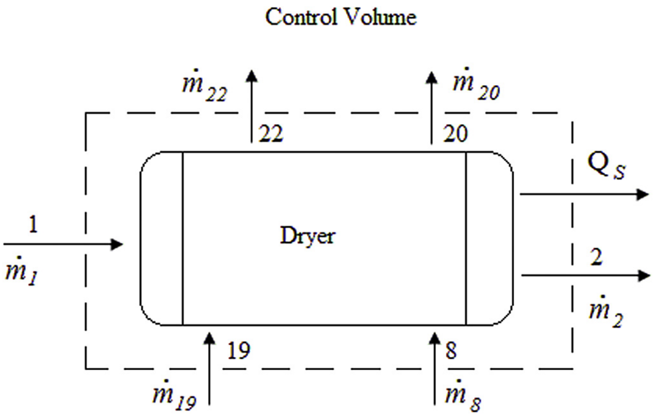

Fig. 5. Control volume of sugarcane dryer.

$$\dot{m}_1 \cdot LHV_{wbg} + Q_{eg} = \dot{m}_2 \cdot LHV_{dbg} + \dot{m}_{steam} \cdot h_{steam} + \dot{m}_2 \cdot Cp_{dbg} \cdot \Delta T + Q_s \tag{5}$$

$$Q_{eg} = \dot{m}_8 \cdot Cp_{eg} \cdot \Delta T - \dot{m}_{19} \cdot Cp_{eg} \cdot \Delta T \tag{6}$$

Fig. 6 shows the interconnection between the installations that compose the Gasification Island, formed by the air blower, the BFBG and the producer gas conditioning system.

Fig. 7 shown the main mass and energy fluxes in the BFBG for the balances in the studied case.

The energy balance in a gasifier using air, oxygen, steam or its mixtures as gasification agent can be determined by Equation (7) [27,28]:

$$\dot{m}_{fuel} LHV_{fuel} + \dot{m}_{air} \Delta h_{air} + \dot{m}_{O_2} \Delta h_{O_2} + \dot{m}_{H_2O}(h_{ve} + \Delta h_{H_2O}) = \dot{m}_{PGas}(\Delta h_{PGas} + LHV_{PGas}) + \dot{m}_{Char}(\Delta h_{char} + LHV_{char}) + \dot{m}_{ashes} \Delta h_{ashes} + Q_G \tag{7}$$

Considering air at standard conditions as gasification agent, and that the gasification occurs at Carbon Boundary Point, i.e. when it is incorporated into the exact amount the gasification agent, ensuring complete gasification of the fuel with no char formation; the energy balance in the analyzed system (Fig. 7) is defined as follows:

$$\dot{m}_2 \cdot LHV_{dbg} + \dot{m}_{air} \Delta h_{air} = \dot{m}_4(\Delta h_{PGas} + LHV_{PGas}) + \dot{m}_5 \Delta h_{ashes} + Q_G \tag{8}$$

The cold gas efficiency using air as gasification agent is given by Equation (9):

$$\eta_{gasifier} = \left(\frac{\dot{m}_4 \cdot LHV_{PGas}}{\dot{m}_2 \cdot LHV_{dbg} + \dot{m}_{air} \Delta h_{air}} \right) \tag{9}$$

The $\eta_{gasifier}$ of the BFBG in this case was considered 75%, a high gasification efficiency for this type of reactors, considering the experimental results reported by several authors [29–32].

The gas turbine selection is performed according to the methodology reported by Antunes, J. [33], using available equipment in the market [34], with an exhaust gas temperature in the range of 773–948 K. In order to keep the mill processes unchanged, the steam parameters at the boiler exit in the CEST configuration must be the same at the exit of the HRSG in the “pure” BIG/GTCC configuration. The gas turbine selection considered an efficiency of the HRSG of 70%, the enthalpy of the fluid at the HRSG entrance (point 14 in Fig. 3) as 454.1 kJ kg^{-1} and the steam enthalpy at exit (point 9 in Fig. 3) as 3488.5 kJ kg^{-1}. The exhaust gases temperature

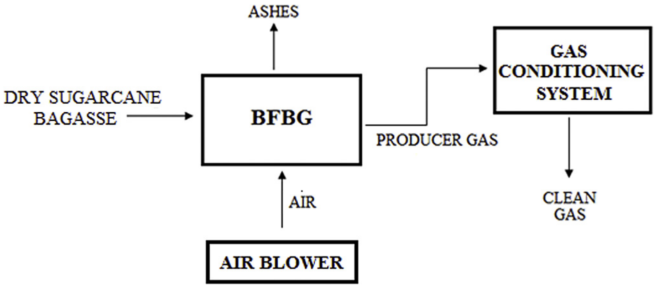

Fig. 6. Components of the Gasification Island using a Bubbling Fluidized Bed Gasifier (BFBG).

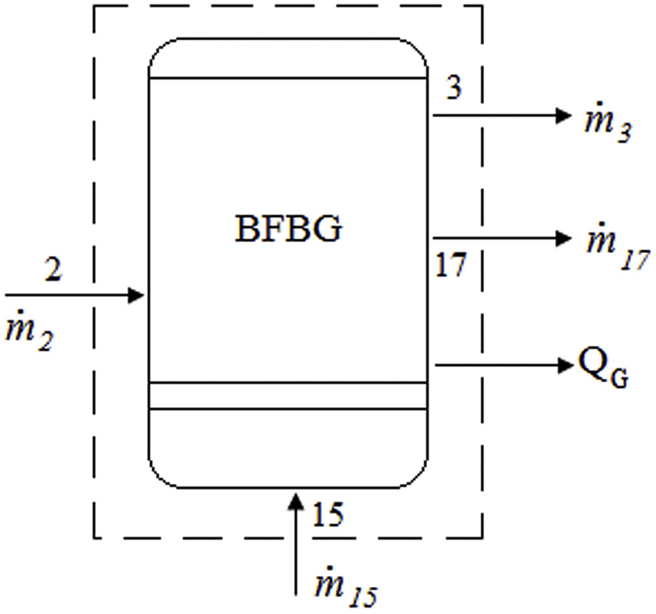

Fig. 7. Main mass and energy fluxes in the BFBG.

must be considered higher than 473 K at the HRSG exit (point 8 in Fig. 3) to avoid condensation problems [35].

The selected gas turbine must have sufficient exhaust gas flow to maintain the steam generation at the HRSG in order to satisfy the energy requirements of the plant.

The selected gas turbine was the Siemens Energy [60 Hz] (model SGT6-5000F) and the operating parameters of the gas turbine were corrected to the following real operating conditions:

- Temperature of 25° C;
- Altitude of 760 m;
- Relative humidity of 60%.

Table 3 shows the characteristics of the selected gas turbine for the local operating conditions.

A gas turbine work can be defined as the product of mass flow, heat energy in the combusted gas and temperature differential across the turbine. Although there is no clear relationship between fuel lower heating value (LHV) and gas turbine power output, it is possible to make some general assumptions. If the fuel consists only of hydrocarbons with no inert gases and no oxygen atoms, output increases as LHV increases. Here the effects of heat energy in the combusted gas are greater than the effects of mass flow. In addition, as the amount of inert gases is increased, the decrease in LHV will provide an increase in power output [36].

Fuel gas with a large amount of inert components [such as carbon dioxide (CO_2) or nitrogen (N_2)] have a low Wobbe index (WI) while substances with a large amount of heavier hydrocarbons have a high WI (Equation (10)), where SG is the relative density of the analyzed gas. For low heating value producer gas, WI range 5–13 MJ. Nm^{-3} while for natural gas in similar thermodynamics conditions the WI range [37] 48–53 MJ. Nm^{-3}.

Table 3
Characteristics of the gas turbine Siemens Energy [60 Hz], (model SGT6-5000F) in simple cycle (SC).

Parameter	Value
Efficiency (%)	38.0
Output (MW)	176.03
Heat Rate (Btu kWh^{-1})	7805.0
Rotation speed (rpm)	3600
Compression ratio	17.2
Exhaust gas flow (kg s^{-1})	477.29
Exhaust temperature [K]	883.47

$$WI = \frac{LHV}{\sqrt{SG}} \tag{10}$$

In general, engines will provide slightly more power output if the Wobbe index is reduced. This is because the amount of fuel mass flow increases for a given amount of fuel energy when reduced the Wobbe index. This increases the mass flow though the turbine section, which increases the power output of the turbine. This is the major impact of IGCC type fuels that have large amounts of inert gas in the fuel [38]. This mass flow addition, which is not compressed by the gas turbine's compressor, increases the turbine power output. Compressor power is essentially unchanged.

In most cases of operation with lower heating value fuels, it can be assumed that power output and efficiency of the gas turbine will be equal to or higher than that obtained on natural gas [36].

To satisfy the steam requirements of the mill using the Siemens Energy [60 Hz], (model SGT6-5000F), firing producer gas, a gasification island with nominal capacity of 600 MW$_{th}$ or higher is necessary, because most commercial-scale gasification islands have a cold gas efficiency of at least [39,40] 65%; in some cases exceed 80%. Note that the cold gas efficiency does not account for the sensible heat available in the syngas, only the chemical energy available.

Special combustors developed by some gas turbine manufacturers can handle cleaned gasified solid and liquid fuels. Burners have been developed for medium heating value fuel (16–20 MJ. Nm^{-3}), which is produced in oxygen-blown gasifiers, and for low heating values fuel (3–5 MJ. Nm^{-3}), which is produced in air-blown gasifiers. These special combustors were developed principally for large gas turbines and are not found on small gas turbines [41].

The reduction in the system electric generation efficiency when lower heating value fuels is used, is basically originated by the additional energy required for the fuel compression, impacting mainly micro-turbines. To avoid this fact, new technology is introducing where, both, producer gas and air are compressed together in the compressor. This does away with the necessity of a costly and inefficient fuel compressor [42].

In the study was considered a reduction of 15% compared to the Gas turbine electricity generation efficiency when Natural Gas is used, based on previous studies [2,41,42]. The energy consumed by the producer gas compressor in this configuration (0.80 MW) was calculated according [42].

Table 4 shows the plant operating parameters for the implementation of the BIG-GTCC "pure" in the mill.

For the calculus of the electricity generation efficiency was used Equation (11), considering the electricity generated in the mill, the energy consumed by the pump of the HRSG and by the producer gas compressor.

$$\eta_{GE} = \frac{E_{tge} + E_{tve} - W_b - W_{LHV}}{E_{comb}} \tag{11}$$

The global efficiency was calculated by Equation (12), considering also the mechanical and thermal energy consumed in the sugar production process.

$$\eta_{GI} = \frac{E_{tge} + E_{tve} + Q_{Proc} + W_{Mec} - W_b - W_{LHV}}{E_{comb}} \tag{12}$$

Table 5 shows a comparison of the generation efficiencies of

Table 4
Results of the energetic analyze for the implementation of the BIG-GTCC "pure" in the mill.

Point	Mass flow [kg s^{-1}]	Temperature [K]	Pressure [kPa]	Energy flow [MW]
1	80.58	298	101.3	589.9
2	56.39	298	101.3	589.9
3	116.2	298	1931	442.4
4	352.45	298	101.3	–
5	352.45	791	1931	–
6	468.65	1563	1834	442.4
7	468.65	860	107	274.94
8	468.65	544	101.3	132.58
9	41.67	803	6468.0	145.4
10	33.53	803	6468.0	116.97
11	5.75	315	8.5	14.82
12	17.78	420.2	245.0	49.06
13	10.0	699	2650.0	32.95
14	41.67	379.8	8820.0	18.92
15	61.48	298	101.3	–
16	–	–	–	167.23
17	1.69	298	101.3	0
18	24.19	373	101.3	64.73
19	468.65	442.6	101.3	77.95
20	–	–	–	0.80

Table 5
Efficiencies of generation of electricity, heat, mechanical and overall energy and total power generated after the implementation of the BIG-GTCC "pure" in the mill.

Technologies	η_{ge}[%]	η_{Qpr}[%]	η_{emec}[%]	η_{gl}[%]	*Ete* [MW]
Conventional	12.9	61.9	2.73	77.5	19.13
BIG-GTCC	27.8	12.9	0.57	43.5	167.23

electricity, heat and mechanical energy, the overall efficiency and the total power generated, between the conventional configuration and when implemented the gasification of the BIG/GTCC "pure".

A variation in the gas turbine performance directly impact in the performance of the proposed configuration. Fig. 8 shows the effect of the variation of gas turbine electricity generation efficiency on electricity and global efficiency for the studied condition.

Is possible observe, that for the lowest gas turbine electricity generation efficiency, the electricity generation efficiency is 10% higher than in the conventional mill configuration.

The gasifier efficiency also is shows as a key parameter for the performance for this type of arrangement. Effects of gasification efficiency variation of on electricity generation efficiency and on sugarcane bagasse consumption (with humidity content between 45 and 50% wet basis) was also analyzed as shows in Fig. 9.

In the range of the cold gas efficiencies analyzed, for the lowest value evaluated, the electricity generation efficiency is twice the value obtained on the conventional configuration. The sugarcane bagasse requirements in this configuration is significantly high for the all cold gas efficiencies analyzed, ranging 3 to 4 times the total bagasse produced in the plant.

The required size of the gasification island is a principal obstacle

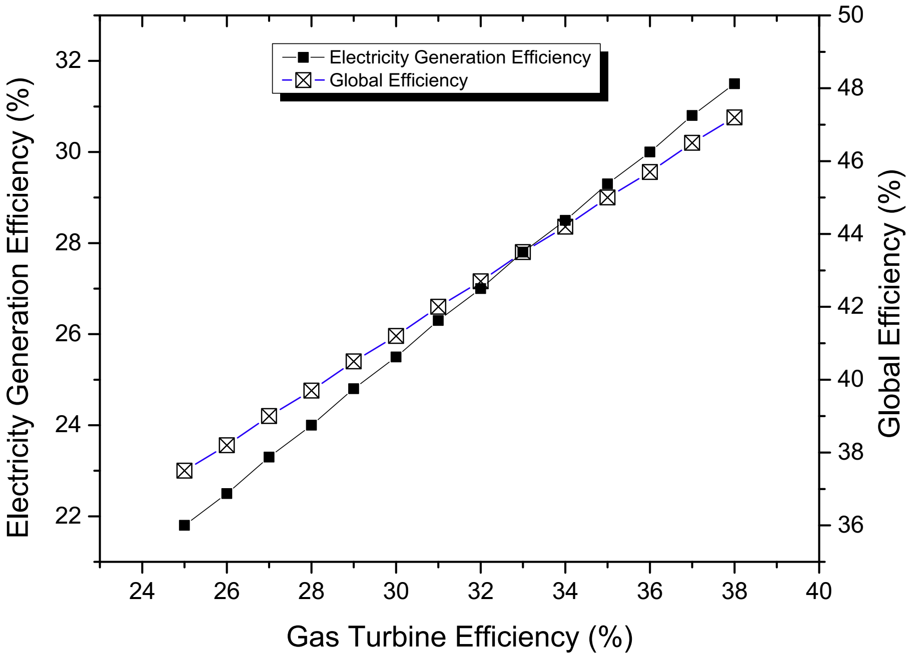

Fig. 8. Effect of variation gas turbine electricity generation efficiency on electricity and global efficiency on Case 1.

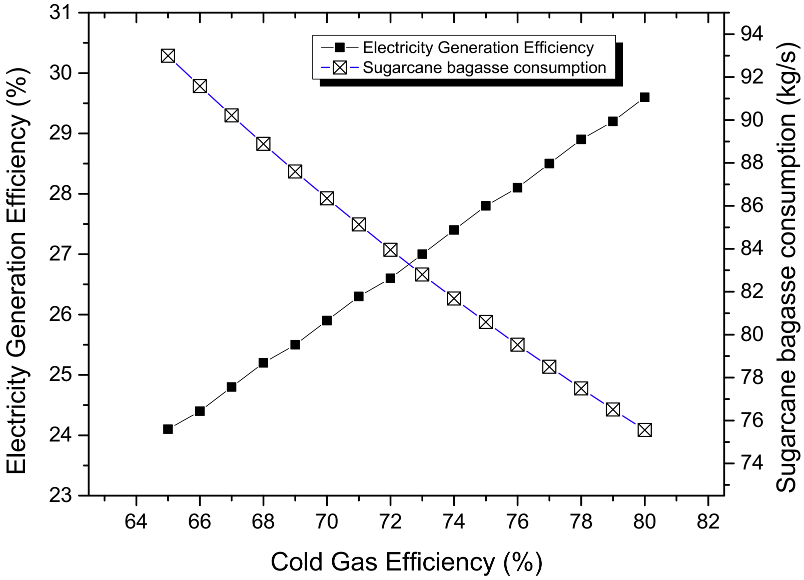

Fig. 9. Effect of variation of cold gas efficiency on electricity generation efficiency and on sugarcane bagasse consumption on Case 1.

for the implementation of the “pure” BIG/GTCC in the baseline sugar mill, since the bigger biomass fluidized bed gasifier available at commercial scale, have a fraction of the required nominal capacity (Table 6). In addition, all the sugarcane bagasse produced in the mill represents 23.1% of the needed biomass to satisfy the feedstock demand of the gasification island.

On this context, the implementation of the “pure” BIG/GTCC in the studied sugar mill could be performed through one of the following configurations:

- **Configuration 1**: A biomass pretreatment unit able to dry 341.36 t h^{-1} of sugar cane bagasse up to 20% (w.b.) of water content, considering 50% wet basis in the raw feedstock; a gasification island composed by seven Circulating Fluidized Bed (CFB) gasifiers, MILENA technology for biomass gasification, with a total nominal capacity of 700 MW$_{th}$, and the producer gas cleaning systems. The gasification island is coupled to a gas turbine Siemens Energy [60 Hz], (model SGT6-5000F). In this configuration (Fig. 3), an external sugarcane bagasse supply of 211.19 t h^{-1} (with 50% humidity content wet basis) is needed (72.7% of the total biomass required) to satisfy the feedstock requirements.
- **Configuration 2**: A biomass pretreatment unit able to dry 78.9 t h^{-1} of sugar cane bagasse up to 20% of water content, considering 50% wet basis in the raw feedstock. A gasification island composed by two Circulating Fluidized Bed (CFB) gasifiers, Foster Wheeler technology for biomass gasification, with a total nominal capacity of 160 MW$_{th}$, and the producer gas cleaning systems. The gasification island is coupled to a gas turbine Siemens Energy [60 Hz], (model SGT6-5000F). In this configuration (Fig. 3), an external natural gas supply of 40.38 t h^{-1}(LHV for a gas natural of 47.14 MJ kg^{-1} [44,45]) is needed (72.79% of the total energy required) to satisfy the turbine feedstock requirements.

The dimensions of the proposed plant in both configurations is the principal obstacle for the economic viability of this configuration, considering an expected plant lifetime of 15 years [39,40]. The required external energy supply to satisfy the plant steam necessities in both cases (72.79%) is also a serious problems for the implementation of the “pure” BIG/GTCC in the studied mill. If a sustainable and economical option to resolve these barriers is applied, there are still reported problems during handling, feeding, gasification and the producer gas cleaning, when using sugarcane bagasse as feedstock [46–48]. In addition, the Institute of Gas Technology (now GTI) in 1988 tested this technology at the Hawaiian Commercial & Sugar Company’s Paia sugar factory in Maui, Hawaii, using 100 t. day^{-1} of sugarcane bagasse as the feedstock to the gasification island. The project demonstrated limited success with air-blown gasification at about 2 MPa (RENUGAS Process) and with the hot-gas filtration to remove carry-over dust. Serious problems were encountered in handling and feeding the shredded

Table 6
Principal commercial projects of biomass gasification islands [39,40,43].

Project Name	Installation Year	Nominal Capacity (MW$_{th}$)	Gasification Technology	Fuel
Carbona	2009	20	BFB	Wood Pellets
Foster Wheeler	2001	40	BFB	Plastics and demolition wood
Energy Products Idaho	1986	28	BFB	Wood Chip
Foster Wheeler (CFB)	2009	160	(2)*CFB	Biomass
VTT Finland	2009	50	CFB	Biomass
ECN	2014	100	CFB	Wood
CHOREN	2013	640	(4)*EFG	Biomass
Karlsruhe Institute of Technology	2006	200	(3)*EFG	Biomass- Agriculture Residues
Uhde PRENFLO Gasification	1992	Up to 1200	EFG	Coal
Westinghouse Plasma	2010	130	Plasma	Biomass, Waste

sugarcane bagasse into the gasifier; the project was terminated in 1997 [49].

To overcome the observed handling and feeding problems when sugarcane bagasse is used as feedstock in biomass gasifiers a second configuration is proposed in the next epigraph.

4.2.2. Case 2: Gasification of bagasse in entrained flow gasifier and the replacement of conventional boiler by BIG-GTCC system, with pre-treatment of bagasse by torrefaction. (BIG-GTCC "pure")

The principal difference of the Case 2, respect the previous analyzed configuration, is the use of torrefaction as pre-treatment process of bagasse, instead drying; and its gasification in an entrained flow gasifier instead a fluidized bed gasifier. The biomass torrefaction is an attractive pre-treatment process, in order to reduce the problems related to the low-density properties of the sugar cane bagasse. The torrefaction may largely improve the energetic properties of this biomass, its milling characteristics, as well as may have a positive impact on transport, handling and storage due to the hydrophobic nature and the physical structure acquired after the torrefaction. Due to the characteristics of the torrefied biomass, mainly heating value and grindability [50,51], its gasification can be carried out using gasification technologies designed to use coal as feedstock. An arrangement of both technologies constitutes the configuration of Case 2, as shown in Fig. 10.

In this configuration, the sugarcane bagasse is fed to the dryer to reduce the water content from 45-50% to 20–25% w. b. The bagasse is then fed to the torrefaction reactor and subsequently to the mill for the sizes reduction of the obtained torrefacted bagasse, which is fed to the gasification island. The volatiles obtained in the torrefaction reactor are also fed to the gasification island to increase the energetic efficiency of the process. The producer gas is then fed to the gas turbine for electricity generation. The gas turbine exhaust gases energy is used part to generate the required steam of the process at the HRSG and part to supply energy for the torrefaction process. A fraction of the sugarcane bagasse is fed to a burner to produce the energy required for the dryer and for the torrefaction process.

Fig. 11 shows the overall mass and energy balances for the torrefaction process of sugarcane bagasse at 250 °C for 30 min, based on the experimental results reported by Pimchuai et al. [51]; it is considered that the provided bagasse has a moisture content of 20–25%.

The concept of torrefaction-aided gasification is similar to two-stage pyrolysis–gasification, but differs in two aspects. Firstly, the temperature of the torrefaction stage is carefully controlled at or below 573 K in order to minimize pyrolysis of cellulose and avoid tar formation. Secondly, the heat requirements for torrefaction are smaller than for pyrolysis at higher temperatures. Therefore, instead of taking heat from the gasifier itself (e.g. by recirculation of hot sand), sufficient heat can be taken from the flue gas as shown in Fig. 10.

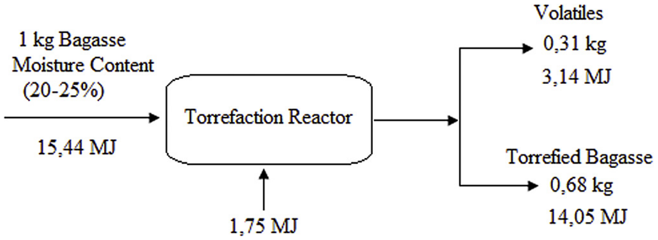

Fig. 11. Overall mass and energy balances for sugarcane bagasse torrefaction process at temperature and reaction time of 250 °C and 30 min (considering the HHV of sugarcane bagasse) [51].

It is possible to observe that after torrefaction, biomass contains 90% of the initial energy and 70% of the initial mass, and the volatiles contain 30% of mass and 10% of the raw fuel energy, causing an energetic densification of the solid product obtained.

The mass and energy balances was performed with base in the same considerations of the Case 1. The energy balance of the torrefaction reactor is determinate by Equations (13) and (14), considering the control volume shows in Fig. 12.

Due to the improved quality of the torrefied sugarcane bagasse (mainly LHV and grindability), is possible to carryout its gasification in a reactor with a higher cold gas efficiency like the entrained flow gasifier (EFG). The cold gas efficiency in the EFG could reach 90% [39,40]. In this case the Gasification Isaland is composed by an Entrained Flow Gasifier, a Cryogenic Air Separation Unit (CASU) and the producer gas conditioning system as shows in Fig. 13.

Fig. 14 shown the main mass and energy fluxes in the EFG for the balances in the studied case.

In this case the cold gas efficiency considered for the calculus was 79% and the energy balance is defined as follows:

$$\dot{m}_2 \cdot LHV_{dbg} + Q_{GE} = \dot{m}_3 \cdot LHV_{bgTorref} + \dot{m}_{12} \cdot (\Delta h_{voláteis} + LHV_{voláteis}) + \dot{m}_{11} \cdot Cp_{GE} \cdot \Delta T + Q_T \qquad (13)$$

$$Q_{GE} = \dot{m}_7 \cdot Cp_{GEC} \cdot \Delta T + \dot{m}_8 \cdot Cp_{GET} \cdot \Delta T - \dot{m}_{11} \cdot Cp_{GE} \cdot \Delta T \qquad (14)$$

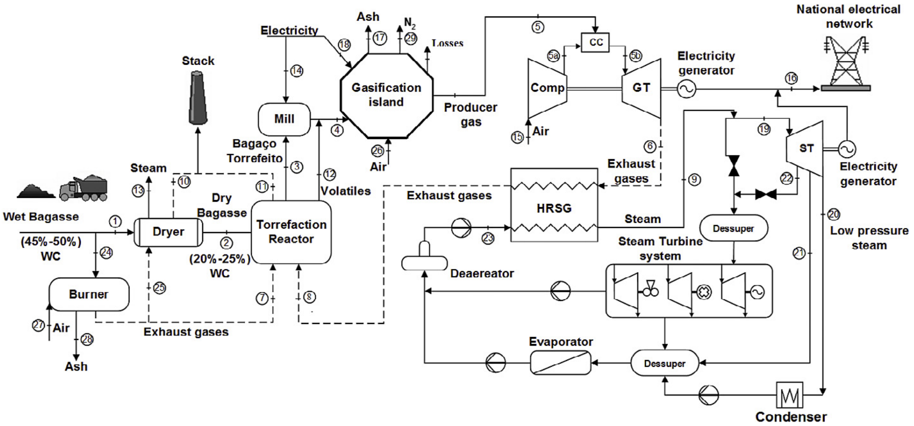

Fig. 10. Simplified schematic of a biomass integrated-gasifier/gas turbine combined cycle system with a torrefaction path (BIG-GTCC "pure").

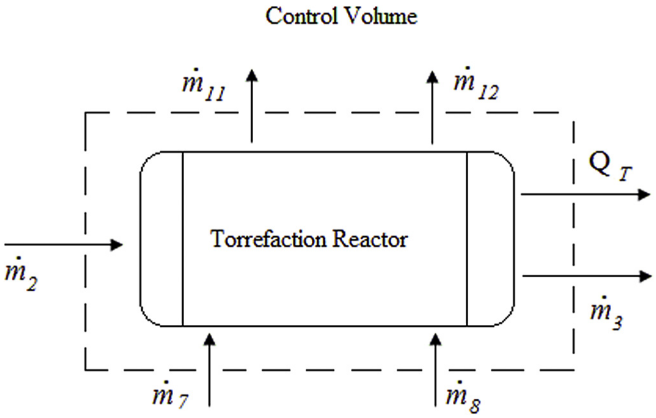

Fig. 12. Control volume of torrefaction reactor.

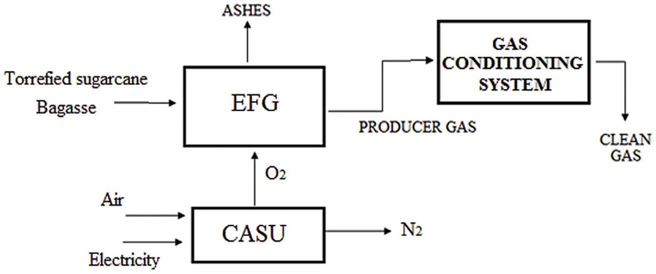

Fig. 13. Components of the Gasification Island using an Entrained Flow Gasifier (EFG).

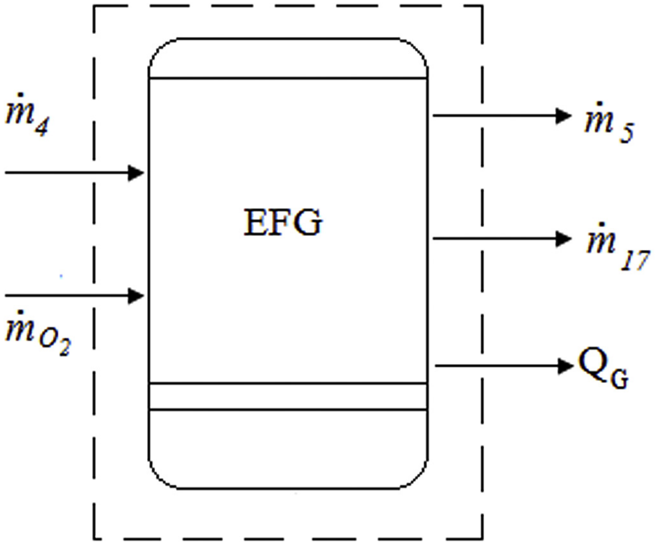

Fig. 14. Main mass and energy fluxes in the EFBG.

$$\dot{m}_3 \cdot LHV_{bgTorref} + \dot{m}_{12} \cdot \left(\Delta h_{voláteis} + LHV_{voláteis}\right) = \dot{m}_5\left(\Delta h_{PGas} + LHV_{PGas}\right) + \dot{m}_{17}\Delta h_{ASHES} + Q_G \quad (15)$$

Table 7 shows the results of the mass and energy balances for the implementation of the BIG-GTCC "pure" with the inclusion of bagasse torrefaction as pretreatment process.

Table 8 shows the generation efficiencies of electricity, heat and mechanical energy and overall efficiency when implemented the gasification of the BIG/GTCC "pure" with pretreatment by torrefaction, considering the energy provided by the sugarcane bagasse.

For the calculus of the electricity generation efficiency in this case was used Equation (16), considering the electricity generated in the plant, the energy consumed by the pump of the HRSG, the producer gas compressor, the mill and the Cryogenic Air Separation Unit.

$$\eta_{GE} = \frac{E_{tge} + E_{tve} - W_b - W_{LHV} - W_{Mill} - W_{CASU}}{E_{comb}} \quad (16)$$

The global efficiency was calculated by Equation (17), considering also the mechanical and thermal energy consumed in the sugar production process.

$$\eta_{GI} = \frac{E_{tge} + E_{tve} + Q_{Proc} + W_{Mec} - W_b - W_{LHV} - W_{Mill} - W_{CASU}}{E_{comb}} \quad (17)$$

In this case was also evaluated the effects of variations in the gas turbine efficiency in the performance of the proposed configuration. Fig. 15 shows the effect of the variation of gas turbine electricity generation efficiency on electricity and global efficiency for the studied condition.

In this configuration occur a sensible reduction in the global and electricity generation efficiency, mainly because of the increments in the electricity consumed by the auxiliary equipment of the systems.

The impact of the variation of cold gas efficiency on electricity generation efficiency and on sugarcane bagasse consumption (with humidity content between 45 and 50% wet basis) was also analyzed as shows in Fig. 16.

The analysis shows that for the range of the cold gas efficiencies evaluated, the sugarcane bagasse required for the implementation of this configuration is increased when compared to the Case 1, with an associated reduction in the electricity and global efficiency; that's mean that for the implementation of this configuration, is needed a biomass pretreatment unit able to dry and torrefy 375.06 t h^{-1} of sugarcane bagasse, considering 50% of water content wet basis in the raw feedstock. Is also required a gasification island composed by an entrained flow gasifier, CHOREN's Carbo-V® process technology, with a nominal capacity of 500 MW_{th}, a Cryogenic Air Separation Unit (ASU), and producer gas cleaning systems. The gasification island is coupled to a gas turbine Siemens Energy [60 Hz], (model SGT6-5000F). In this configuration (Fig. 10), an external sugarcane bagasse supply of 264.92 t h^{-1} is needed (77.05% of the total biomass required) to satisfy the feedstock requirements.

The principal obstacle for the viability for the implementation of the "pure" BIG/GTCC with this configuration is the required external energy supply to satisfy the plant steam necessities, equivalent to all the produced sugarcane bagasse of four sugar mill with similar processing capacity of the studied mill. In the sugar mills with smaller steam requirements, the Case 2 could be evaluated for the viability of its implementation. An increase of the electricity generation efficiency without a significant increase in the sugarcane bagasse requirements is the main objective of the case 3 analyzed in the next epigraph.

4.2.3. Case 3. Implementation of the "partial" BIG/GTCC system in the sugarcane industry

In this case the BIG/GTCC implementation will not affect the baseline configuration of the plant and use as feedstock the surplus bagasse of the plant, differently than the earlier cases. The implementation of the "partial" BIG/GTCC, combined with a sugarcane

Table 7
Results of the mass and energy balances for the implementation of the BIG-GTCC "pure" with bagasse torrefaction.

Point	Mass flow [kg s^{-1}]	Temperature [K]	Pressure [kPa]	Energy flow [MW]
1	68.05	298	101.3	498.19
2	47.64	333	101.3	498.19
3	33.34	373	101.3	453.36
4	47.64	373	101.3	553.01
5	56.31	323	1931	442.40
6	468.65	860	107	275.17
7	10.74	1278.93	101.3	12.11
8	468.65	544	101.3	132.58
9	41.67	803	6468.0	145.4
10	75.89	552.94	101.3	22.25
11	479.39	474.04	101.3	97.05
12	14.29	373	101.3	99.64
13	20.42	373	101.3	54.64
14	–	–	–	2.27
15	412.34	298	101.3	0
16	–	–	–	167.23
17	2.88	298	101.3	0
18	–	–	–	16.7
19	33.53	803	6468.0	116.96
20	5.75	316	8.5	14.82
21	17.78	420.3	245	49.05
22	10	699.3	2650.0	32.95
23	41.67	380.1	8820.0	18.92
24	15.19	298	101.3	111.25
25	75.89	1278.93	101.3	76.89
26	48.10	298	101.3	0
27	71.66	298	101.3	0
28	0.23	373	101.3	40.19
29	36,55	298	101.3	–

Table 8
Efficiencies of generation of electricity, heat, mechanical and overall energy and total power generated with the implementation of BIG/GTCC "pure" with pretreatment by torrefaction.

Technologies	η_{ge}[%]	η_{Qpr}[%]	η_{emec}[%]	η_{gl}[%]	*Ete* [MW]
Conventional	12.9	61.9	2.73	77.53	19.13
BIG-GTCC	23.9	12.7	0.56	39.1	167.23

bagasse torrefaction, appear to be better alternative; due to the elevated investments and to the large external supply of energy required for the implementation of the studied "pure" - BIG/GTCC configurations. In the "partial" BIG/GTCC the existing cogeneration equipment at the mill, provides the process steam requirements. The "partial" BIG/GTCC configuration proposed for the studied mill is shown in Fig. 17.

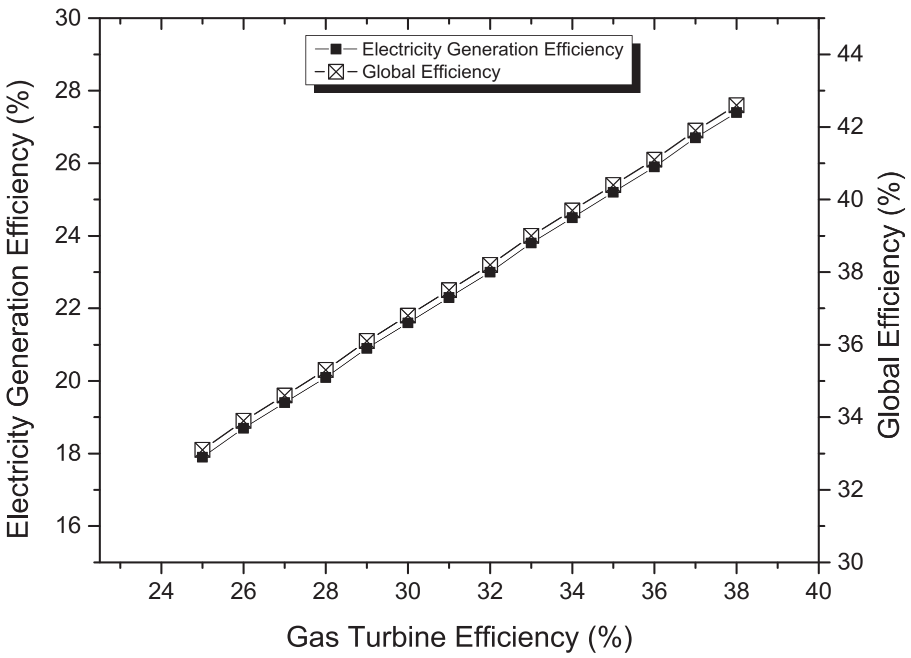

Fig. 15. Effect of variation gas turbine electricity generation efficiency on electricity and global efficiency on Case 2.

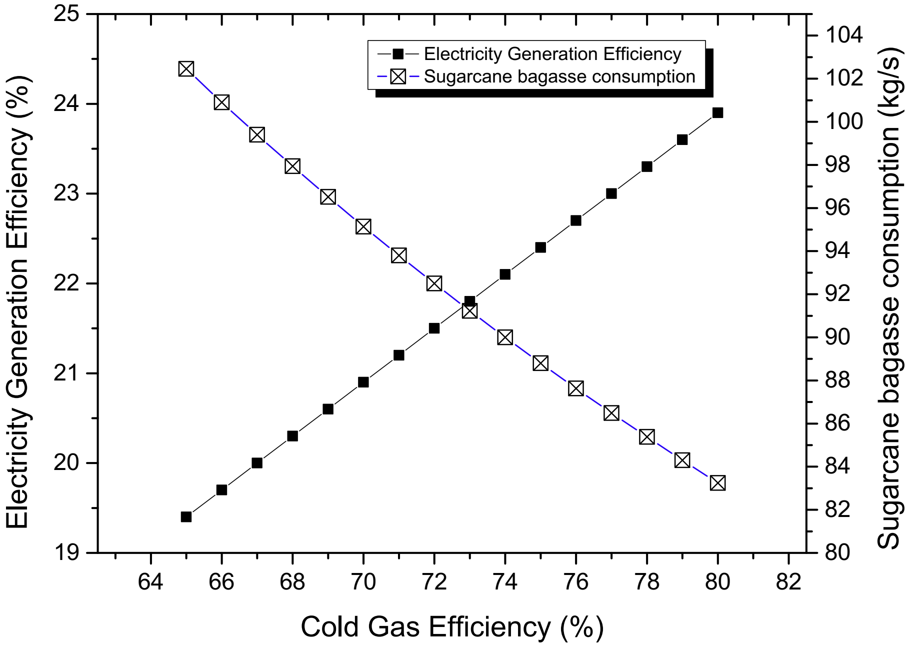

Fig. 16. Effect of variation of cold gas efficiency on electricity generation efficiency and on sugarcane bagasse consumption on Case 2.

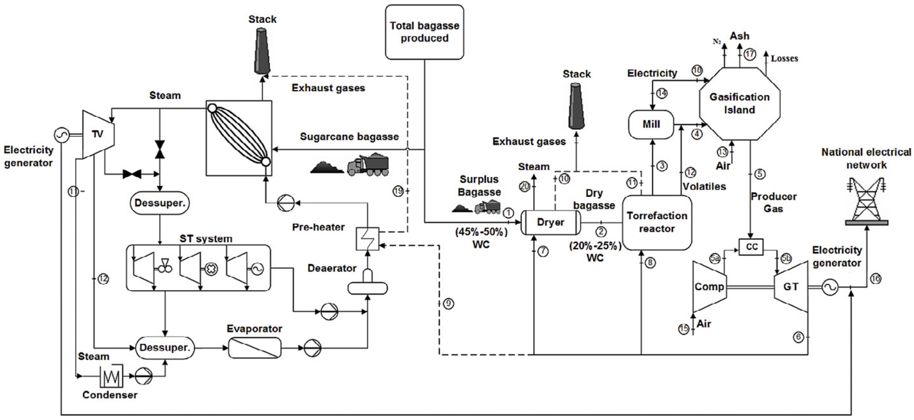

Fig. 17. Surplus bagasse gasification in entrained flow gasifier, considering the pretreatment of bagasse by torrefaction. (BIG-GTCC "Partial").

The installed boiler to generating 150 t h^{-1} of steam at 6468 kPa and 803 K of temperature, and the turbo generator, generating 19.127 MW of electricity with the high-pressure steam from the boiler, with a multistage turbine of extraction and condensation; this facilities provides the process steam requirements. In parallel, a biomass pretreatment unit able to dry and torrefy 8.4 t h^{-1} of sugarcane bagasse, considering 50% of water content wet basis in the raw feedstock, to feed a gasification island. The gasification island is composed by an entrained flow gasifier, CHOREN Carbo-V® process technology [52]; with a nominal capacity of 20 MW_{th}, a Cryogenic Air Separation Unit (CASU), and the producer gas cleaning systems. The gasification island is coupled to a gas turbine Rolls Royce (model 501-KH5). (Fig. 17).

The "partial" BIG/GTCC configuration with a biomass torrefaction path as pretreatment process have several advantages over the "pure" BIG/GTCC configuration. This arrangement allows the electricity generation increment, without modifications in the existing mill facilities. The design dimensions of the BIG/GTCC arrangement will be only determined by the available sugarcane bagasse (surplus bagasse of the process or supplied by an external provider). The implementation of this configuration also allows the electricity generation in milling season and off season using another biomass as feedstock.

The mass and energy balances was performed with base in the same considerations of the Case 2. The energy balance of the torrefaction reactor is determinate by Equations (18) and (19), considering the control volume shows Fig. 18.

Similarly to the considered in the Case 2 the improved quality of the torrefied sugarcane, the gasifier proposed is an the entrained flow gasifier (EFG); also the Gasification Isaland is compoused by an Entrained Flow Gasifier with a cold gas efficiency of 79%, a Cryogenic Air Separation Unit (CASU) and the producer gas conditioning system as shows in Fig. 17. The main mass and energy fluxes in the EFG are similar to the shows in Fig. 14 and the energy balance is governing by Equation (15).

Table 9 reports the results of the mass and energy balances of the "partial" BIG/GTCC in the studied sugar mill, with the surplus sugarcane bagasse of the process (8.4 t h^{-1}) with humidity content

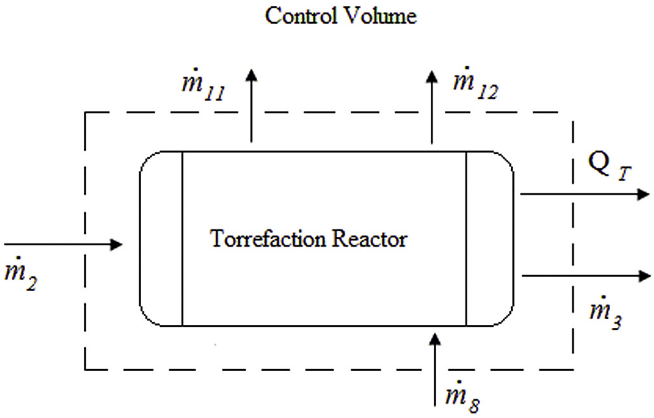

Fig. 18. Control volume of torrefaction reactor.

$$\dot{m}_2 \cdot LHV_{dbg} + Q_{GE} = \dot{m}_3 \cdot LHV_{bgTorref} + \dot{m}_{12} \cdot (\Delta h_{\text{voláteis}} + LHV_{\text{voláteis}}) + \dot{m}_{11} \cdot Cp_{GE} \cdot \Delta T + Q_T \qquad (18)$$

$$Q_{GE} = \dot{m}_8 \cdot Cp_{GET} \cdot \Delta T - \dot{m}_{11} \cdot Cp_{GE} \cdot \Delta T \qquad (19)$$

Table 9
Results of the mass and energy balances of the "partial" BIG/GTCC.

Point	Mass Flow (kg s^{-1})	Temperature (K)	Pressure [kPa]	Energy flow [MW]
1′	2.33	298	101.3	17.05
2′	1.30	333	101.3	17.05
3′	0.88	353	101.3	15.41
4′	0.88	313	101.3	15.41
5′	1.51	1073	1931	15.59
6′	18.42	803	107	9.20
7′	7.77	803	107	3.88
8′	7.92	803	107	4.00
9′	2.73	803	107	1.32
10′	7.77	552	101.3	1.55
11′	7.92	550.5	101.3	1.6
12′	0.40	394	101.3	4.08
13′	1.26	298	101.3	–
14′	–	–	–	0.28
15′	16.89	298	101.3	–
16′	–	–	–	6.23
17′	0.03	298	101.3	0
18′	–	–	–	0.62
19′	2.73	480.5	101.3	0.26
20′	1.03	373	101.3	2.33

of 50% wet basis and LHV of 7.32 MJ kg^{-1}. Was considered a torrefaction reactor efficiency of 60% [53].

According to the results reported in Table 9, the implementation of the Case 3 will permit a net generation of 5.33 MW_e for the commercialization, using the surplus bagasse of the studied plant. This configuration also allows preheating the water at the boiler entrance, using the gas turbine exhaust; improving the overall efficiency of the plant. The high cool gas efficiency obtained with the use of CHOREN Carbo-V® gasification technology, and the capacity to gasify the rich tar gas, produced during the torrefaction, permit that the introduction of the torrefaction process for the biomass pretreatment, not cause a significant reduction of the plant efficiency. The introduction of HRSG and a steam turbine for electricity generation, in combine cycle with the gas turbine, could increase the generation efficiency of the plant, but an external source of energy will be required for drying and torrefaction process.

For the calculus of the electricity generation efficiency in this case was used Equation (16), considering the electricity generated in the plant, the energy consumed by the pump of the boiler, the producer gas compressor, the mill and the Cryogenic Air Separation Unit. The global efficiency was calculated by Equation (17), considering also the mechanical and thermal energy consumed in the sugar production process.

Table 10 shows the efficiencies of generation of electricity, heat and mechanical energy and global when implemented the gasification of the BIG/GTCC "partial" with pretreatment by torrefaction, considering the energy provided by the sugarcane bagasse. The electricity generation efficiency in this case was 14.7%.

Fig. 19 shows the impact of gas turbine efficiency variations in the in the performance of this configuration. Different to the previous studied cases, there is a small variation on electricity generation efficiency and global efficiency for the studied conditions, ranging up to 1.5% for both.

For the lower analyzed gas turbine efficiency, the electricity generation efficiency approaching to the efficiency obtained in the baseline configuration; not justifying the implementation of this configuration if is expected that the gas turbine have that efficiency.

The impact of the variation of cold gas efficiency on electricity generation efficiency and on sugarcane bagasse consumption (with humidity content between 45 and 50% wet basis) was also analyzed as shows in Fig. 20.

The analysis shows that for the interval of cold gas efficiencies from 88 to 78%, not additional sugarcane bagasse is required for the implementation of this configuration increasing approximately 2% in the electricity generation efficiency. For lower efficiency increases of sugarcane bagasse requirement and a small growth of electricity generation is observed.

Table 10
Efficiencies of generation of electricity, heat, mechanical and overall energy and total power generated when gasified the bagasse surplus volume in the plant.

Technologies	η_{ge}[%]	η_{Qpr}[%]	η_{emec}[%]	η_{gl}[%]	E_{te}[MW]
Conventional	12.9	61.9	2.73	77.53	19.13
BIG-GTCC	14.7	55.31	2.44	72.4	24.30

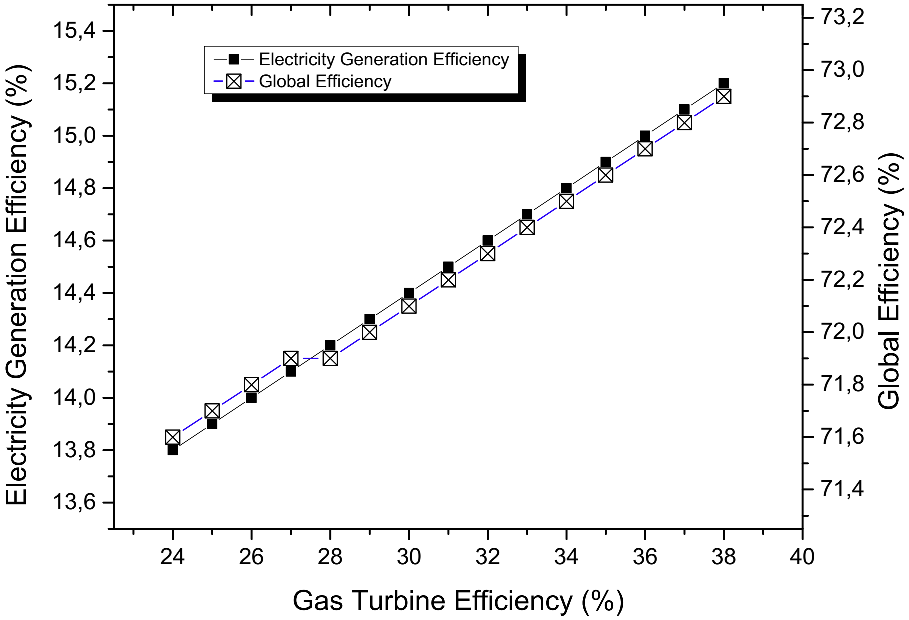

Fig. 19. Effect of variation gas turbine electricity generation efficiency on electricity and global efficiency on Case 3.

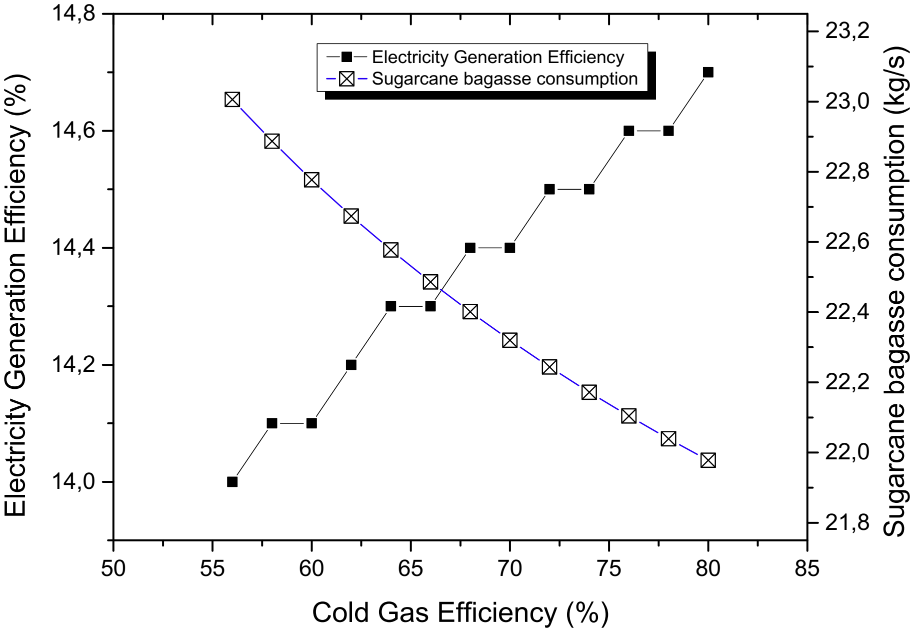

Fig. 20. Effect of variation of cold gas efficiency on electricity generation efficiency and on sugarcane bagasse consumption on Case 3.

5. Comparative technical analyze of three studied cases

Fig. 21 shows a comparison of electricity generation efficiency and overall efficiency of baseline configuration with the expected after implementation of all considered configurations of the BIG-GTCC technology.

In all cases, an increment in the power generation efficiency is observed after the implementation of gasification process compared to the conventional cycle. The implementation of BIG-GTCC “pure” with and without torrefaction shows a significant increases.

The implementation of the “partial” BIG-GTCC, gasifying the surplus bagasse of the plant, appears as a more attractive alternative. The combination of the torrefaction pre-treatment process and the entrained flow gasifier type CHOREN Carbo-V® technology allows an electrical generation efficiency of up to 14.7%, without decreasing the overall efficiency when compared with the conventional cycle. An improve on the gas turbine performance, can increase the electrical generation efficiency of this configuration up to 15.2%.

6. Conclusions

An assessment of three probable scenario for the integration of BIG/GTCC to the studied sugar mill was conducted. In Case 1, the bagasse is gasified, rather than being burnt as in the conventional

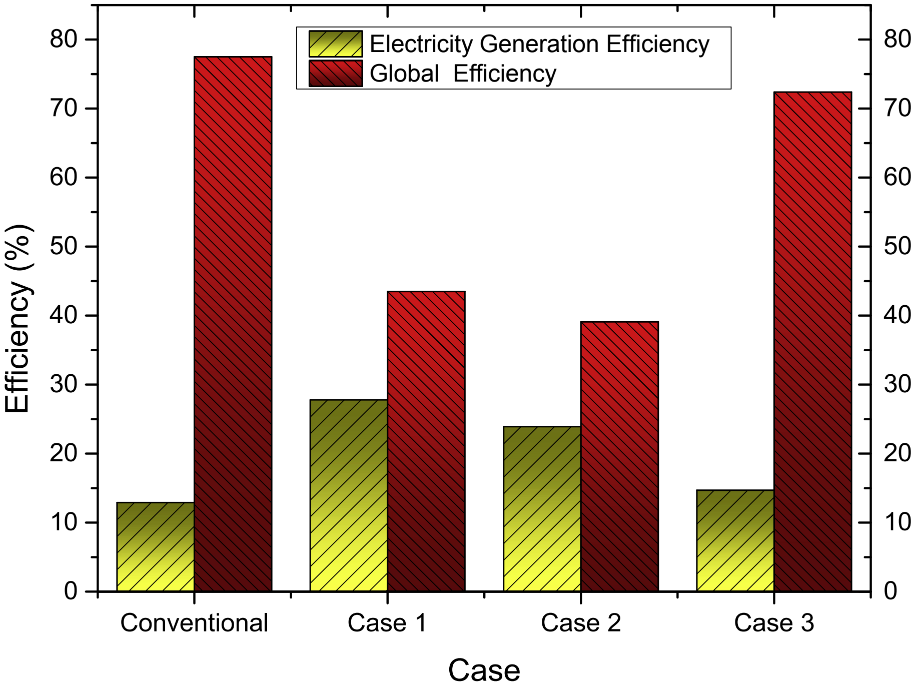

Fig. 21. Comparison of electricity generation efficiency and global efficiency of conventional power plant configuration with the expected after implementation of all considered configurations of the BIG-GTCC technology.

cycle, replacing the conventional boiler by gasifier – gas turbine and HRSG assembly; were analyzed two possible configurations according to the technologies available in the market. In Case 2, was considered the possibility of gasification the bagasse in the plant in entrained flow gasifier and the replacement of conventional boiler by BIG-GTCC system, with the introduction of torrefaction as pre-treatment process of sugarcane bagasse. In Case 3, was considered the gasification of surplus bagasse in entrained flow gasifier after the torrefaction as pre-treatment process. The results indicates that for sugar plants, with large steam requirements, the implementation of the “pure” BIG/GTCC, (Case 1 and 2) is not convenient due to the size of the required gas turbine and consequently the dimensions of the needed gasification island.

The implementation of the “partial” BIG/GTCC appear to be better alternative. The combination of the torrefaction pretreatment and entrained flow gasifier, CHOREN Carbo-V® type, could permit an electric generation efficiency of 14.7% and the increment of the CEST cogeneration efficiency, using wet sugarcane bagasse as feedstock. An economic study must be performed to analyze the viability of the implementation of the proposed configuration in the Case 2 and 3.

Acknowledgments

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