Technical and Economical Analysis of Biomass Integrated Gasifier/ Combined Cycle Power.

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Abstract: *The obtained energy from the biomass is considered one of the main energy sources for the sustainable development, mainly for the developing countries. Its use in heat and electricity combined generation systems (cogeneration) or in thermoelectric plants operated via combined cycle, has been recommended in various applications due to the high levels of conversion efficiencies. In this case, the biomass must be gasified and cleaned to produce synthesis gas used in power systems such as gas turbines and steam turbines. Nowadays, the biomass is responsible for 10 to 14% of the world energy production. The biomass gasification is a process conversion of this energy source that brings many environment benefits, reducing pollutants emissions. The aim of this work is to design a Gasifier integrated into a combined cycle generation plant. The first combined cycle system consists a Gas Turbine PG5371 (26.300,00 MW) associated with a heat recovery steam generator without supplementary burning (SQS) supplying a Steam Turbine ALSTOM (ST-2) (10.000,00 MW). The second combined cycle system consists a TG-2500 (21.960,00 MW) associated with a heat recovery steam generator with supplementary burning (CQS) supplying the same steam turbine. Based on gas turbine data, the fluidized bed gasifier was selected. Values of the mass and energy balance are presented. The lower heat value of the synthesis gas obtained was 5.565,45 kJ/Nm^3, which is within the range accepted by some authors (Lora and Nogueira, 2003) (4.000,00 – 6.000,00 kJ/Nm^3). The operation temperature of the synthesis gas is 800 ºC. The cold efficiency for SQS system is 79,34% and for CQS system is 65,37%. For combined cycle the efficiency value for SQS system was 49,29% and CQS system was 67,05%. In addition, the electricity production cost, expected annual revenue was determinate, considering the investments in emission technologies control, and the brazilian rural zones electricity price since 2007 (0,1078US$/kWh).*

Key Words: Gasification, Combined Cycle, Technical and Economical Analyze, Biomass.

1. INTRODUTION.

The gasification process transforms a solid material into fuel gas, through its partial oxidation at high temperatures. The process produces gas, mainly containing CO (9 - 21%), H_2 (6 - 19%), CH_4 (3 - 7%) (Lora and Nogueira, 2003). The gasification is a heterogeneous reaction type gas - solid. The oxidant agents are presents in the gasification process such as: air, oxygen, carbon dioxide, water steam, etc. The syngas was applied in different systems, for example: In Combustion Motors (MCI) and Gas Turbines, the extensive cleaning of the gas is very important and strict to guarantee the quality of operation of the system. In "Table 1" are presented data related to the quality of gas to be employed in the systems mentioned before.

Table 1. Gas quality use in systems of energy generation.

	MCI	**Turbine**
Particulate (mg/Nm^3)	50 (maximum)	30 (maximum)
Size of particle (µm)	10 (maximum)	5 (maximum)
Tar (mg/Nm^3)	100 (maximum)	-
Alkaline Metals (mg/Nm^3)	-	0,24

In a Combined Cycle (CC), the exhaust gas of gas turbine operate at high temperature in the heat recovery steam generator (HRSG) to produce superheated steam, which is utilized, in a second generator which is coupled with a steam turbine. One of the applications of CC is in the Biomass Gasification Processes, known as Biomass Integrated Gasification Combined Cycle (BIGCC). This system increases efficiency of the process. In the "Fig. 1" a scheme of BIGCC is presented.

2. DESCRIPTION OF SYSTEM

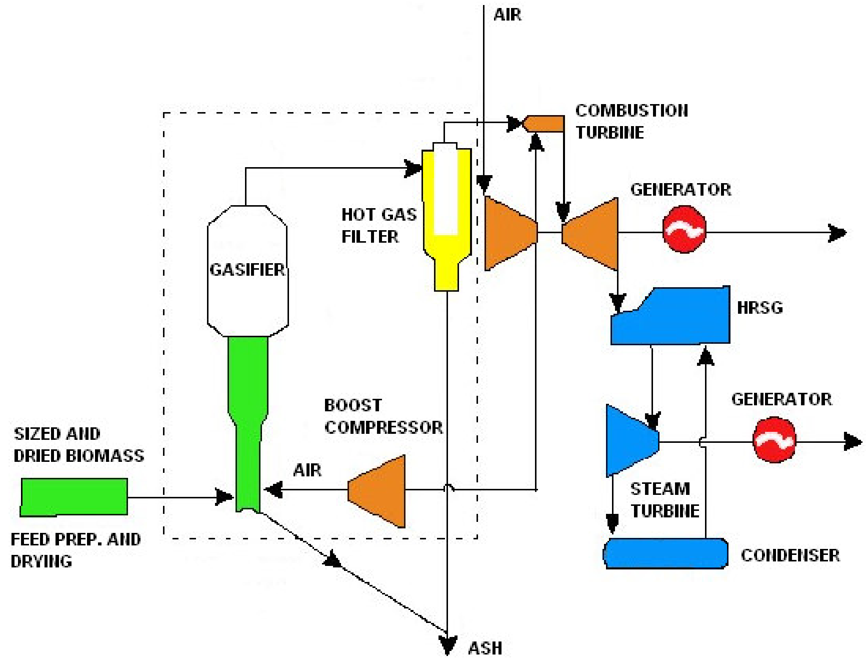

Figure. 1. Biomass Integrated Gasification Combined Cycle (BIGCC)

Figure 1 shows a description of the studied system in this paper. This system contains three stages: The first stage includes the process of Biomass Gasification, the second stage explains the cleaning process of syngas, and a third stage includes the process of electricity generation. In the first stage, air in the ISO conditions was used by boost compressor, sending a percentage into the Combustion Chamber and the rest was injected into the bed region of Gasifier to keep particles in suspension (Becerra, 1999), before gasification process, the biomass was sized and dried. The Gasifier produces syngas at 800 °C. In the second stage the syngas was cleaned in a Hot Gas Filter to eliminate particulate material contained in the syngas. In the third stage the syngas burning reacting with air in the combustion chamber is occurred. The values of air and gas flow appear in the "Table 10". In the "Table 5" the characteristic of Gas Turbine was used in system were appeared. The exhaust gas from the gas turbine exchange heat with water in the Heat Recovery Steam Generator (HRSG) to produce super heat steam at 8,0 MPa and 480 °C. The value of escape gas temperature in the HRSG is 132,40 °C. The super heat steam is inserted into the steam turbine, expanding to saturation conditions at 1 MPa and 179,90 °C. Under these conditions the super heat steam arrives in the condenser where the heat exchanges with the environment water to produce saturated liquid. Ultimately, the pump sends saturated liquid to the HRSG.

3. METHODOLOGY

3.1 Selection of Combined Cycle, Steam and Gas Turbine.

The demand value for electricity generation is 30 MW in the region where the installation of the system is required. The characteristics of selected Steam Turbine selected appear in "Table 2".

Table 2. Data for Steam Turbine Alstom

Type	Power Rate (MW)	Inlet Temperature (ºC)	Inlet Pressure (MPa)	Exhaust Pressure (MPa)
ST2	10	480	8	1

Based on the Law of Energy Conservation to a control volume (see Eq. (1)), exceeding kinetic and potential energy the value of the steam flow generated in the HRSG, the heat flow lost in the condenser, the energy consumed by the pump and the gas flow required by the HRSG were calculated. The value of gas flow in HRSG was calculated based on the supplementary burning (30% of Consumed Energy by Combustion Syngas in Combustion Chamber) and without supplementary burning, with this gases flow and choice of some GE temperatures values (400 ºC up to 700 °C) two graphics (see "Fig. 2" and "Fig. 3") were calculated.

$$Q_{VC} + \sum_{I=1}^{N} M_I \times H_I = W_{VC} + \sum_{O=1}^{N} M_O \times H_O \quad (1)$$

$$M_G = \frac{M_S \times (H_{SHS} - H_{SL})}{0{,}70 \times Cp_G \times (T_{GI} - T_{GO})} \quad \text{(SQS)} \tag{2}$$

$$M_G = \frac{M_S \times (H_{SHS} - H_{SL}) - (0{,}21 \times E_{COMB})}{0{,}70 \times Cp_G \times (T_{GI} - T_{GO})} \quad \text{(CQS)} \tag{3}$$

Where:

Qvc	Heat Flow in control volume (kW)	Mg	Inlet gas flow in HRSG (kg/s)	Mo	Outlet Mass Flow
Mi	Inlet Mass Flow (kg/s)	Ms	Steam Flow (kg/s)	Ho	Outlet Enthalpy
Wvc	Work in control volume (kW)	Hshs	Superheated Steam Enthalpy (kJ/kg)	CPg	Specific Heat of Gas (kJ/kg ºK)
Hi	Inlet Enthalpy (kJ/kg)	Hsl	Saturated Liquid Enthalpy (kJ/kg)	Tgi	Inlet Temperature of Gas in HRSG (ºK)

Table 3. Calculated values of Heat Flow, Work for Syngas in each examined system.

Parameter	Steam Turbine	Condenser	Pump	Combustion Chamber	
Work (kW)	9500,00	-	-9236,67	-	
Heat Flow (kW)	-	-33586,67	-	92392,91	
Steam Flow (kg/s)	16,67			-	
Syngas Flow (kg/s)	-			SQS	CQS
				1,31	1,08

Table 4. Values of gas flow and temperature in HRSG

System	Gas Flow (Kg/s)		Gas Temperature (K)
	SQS	CQS	
Heat Recovery Steam Generator (HRSG)	174,26	107,83	673
	124,47	77,02	773
	96,81	59,91	873
	79,21	49,01	973

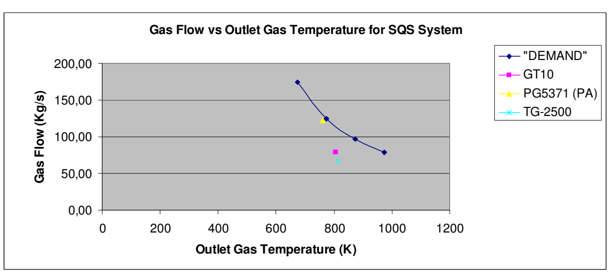

Figure. 2 Gas Flow vs. Outlet Temperature in Gas Turbine (SQS).

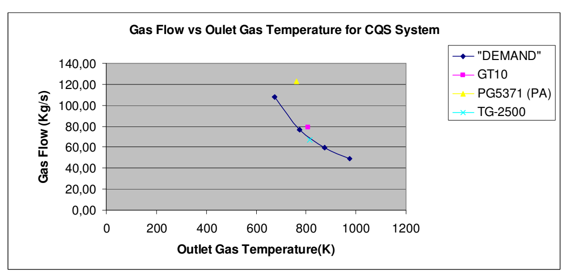

Figure. 3 Gas Flow vs. Outlet Temperature in Gas Turbine (CQS).

For System SQS (see “Fig. 2”) a Gas Turbine PG5371(PA) was selected, because the value of gas flow of this turbine is found near the value of reference curve (Demand). For System CQS (see “Fig. 3”) a Gas Turbine TG-2500 was selected due to the same purpose cited previously. Data’s of turbines are showed in “Tab. 5”.

Table 5. Gas Turbines.

Type	E_{PTG} (kW)	HR (BTU/kWH)	Pp	Mg (kg/s)	Outlet Temperature (K)
GT10	24630	9970	14	78,64	807
PG5371 (PA)	26300	11990	10,2	122,73	760,37
TG-2500	21960	9550	18,8	67,27	815,37

In "Tab. 6" the calculated value of efficiency in system for each cycle is showed.

Table 6. Efficiency Values.

Cycle	Efficiency (%)	
	CQS	SQS
Steam Turbine	31,31	20,82
Gas Turbine	35,74	28,47
Combined	67,05	49,29

$$\eta_{TG} = \frac{E_{PTG}}{E_{COMB}} \tag{4}$$

$$\eta_{TV} = \frac{E_{PTV} - W_B}{E_{COMB}} \tag{5}$$

$$E_{COMB} = \frac{E_{PTG} \times HR}{3413} \tag{6}$$

Where:
ηtg: Gas Turbine Efficiency (%)
ηtv: Steam Turbine Efficiency (%)
Eptg: Gas Turbine Power (kW)
Eptv: Steam Turbine Power (kW)
Wb: Pump Work (kW)
HR: Heat Rate (BTU/kWh)

3.2 Selection of Gasifier based in Supplementary Burning and Without Supplementary Burning Concepts.

3.2.1 Gasification Process and Type of Gasifier.

The gasifier to be used in BIG-CC system is Circulating Fluidized Bed (CFB). This gasifier was employed for large plants, and the found biomass flow was 16,1 ton/h (Coronado, 2006). In this paper the value of biomass flow is between 16,34 to 16,52.

3.2.2 Stoichiometric calculation in gasification region.

The stoichiometric analysis was used to calculate a gas density for syngas, and value of relation air/biomass. In "Tab. 7" the biomass composition (eucalipto) is showed (Coronado, 2006).

Table 7. Biomass Composition.

Component	Composition (%)	Atomic Mass	Stoichiometric mass of Fuel (mol_{COMB})
H	5,87	2	5,8700
C	49	16	4,0833
S	0,01	28	0,0003
N	0,3	28	0,0214
O	43,97	32	2,7481
Total			12,72

Table 8. Values of atomic balance

C	X	4,08
H	Y	2,94
O	A	8,35
N	Z	31,42
S	W	0,0003

The value of Equivalence ratio Air/Biomass (ER) is 0,22. The found value is in range of studied values by different authors (Lora and Nogueira, 2003). The Eq. 7 (Becerra, 1999) is used to calculate the theory air (Ma^0) for gasification process. The Eq. 8 is used to calculate a Factor Air/Biomass (FA).

$$Ma^0 = 0{,}0889(C^t + 0{,}375S^t) + (0{,}265H^t) - (0{,}0333O^t) \tag{7}$$

$$FA = \frac{R_{a/b}}{Ma^0} \tag{8}$$

3.2.3 Mass Balance in Gasifier

The value of outlet ash flow was obtained employing Eq. (9). In "Tab. 9" the balance values is showed.

$$M_{ASH} = M_B + M_{AIR} - M_{GST} \tag{9}$$

Where:

M_{AIR}	Air flow in gasification area
M_B	Biomass Flow
M_{GST}	Syngas Flow
M_{ASH}	Outlet Ash Flow

$$M_B = \frac{M_{AIR}}{M^o \times ER} \tag{10}$$

$$M_{AIR} = A_{BED} \times V_{SL} \times \rho \tag{11}$$

Where:

ER	Equivalence Ratio
A_{BED}	Bed Area (m^2)
V_{SL}	Superficial Particulate Velocity in the Bed (m/s)
ρ	Air Density (kg/m^3)
M^o	Stoichiometric Ratio Air/Dry Biomass

The diameter of bed is 3 m, the value of superficial velocity of particles is 8,5 m/s (Lora e Nogueira, 2003), the value of Ma^0 is 1,83.

Table 9. Values for mass balance in the gasifier.

Flow	**U/M (kg/s)**	
	SQS	**CQS**
M_{AIR}	4,82	4,82
M_B	4,59	4,54
M_{GST}	1,31	1,08
M_{ASH}	8,10	8,28

3.2.4 Energy Balance in Gasifier, Cold and Heat Efficiency.

$$M_B \times H_B + M_{AIR} \times H_{AIR} = M_{GST} \times H_{GST} + M_{ASH} \times H_{ASH} + Q_E \tag{12}$$

Where:

Q_E	Loss heat into the environment (kW)
H_B	Biomass Enthalpy (kJ/kg)
H_{GST}	Syngas Enthalpy (kJ/kg)
H_{AIR}	Air Enthalpy (kJ/kg)
H_{ASH}	Ash Entalphy (kJ/kg)

$$LHV_G = (0{,}126 \times C_{CO} + 0{,}358C_{CH4} + 0{,}108 \times C_{H2} + 0{,}59 \times C_{C2H4} + 0{,}637 \times C_{C2H6}) \times 1000 \tag{13}$$

The value of LHV_G (5565,45 kJ/Nm^3), is found in the studied range values by same authors (Lora and Nogueira, 2003).

$$H_G = C_{CO2} \times H_{CO2} + C_{CH4} \times H_{CH4} + C_{H2} \times H_{H2} + C_{N2} \times H_{N2} + C_{O2} \times H_{O2} + C_{CO} \times H_{CO} + C_{H2O} \times H_{H2O} \quad (14)$$

Table 10. Syngas Composition and volumetric concentration.

Component	Composition (%)
CO_2	13,4
C_2H_4	0,19
C_2H_6	0,15
C_2H_2	0,01
H_2	17,9
O_2	0,90
N_2	48
CH_4	3,6
CO	13,4
H_2O	10,60

The enthalpy (see "Eq. (15)") of each element gas must be determinate with specific heat (Perry, 1984). The value of operation temperature is 800 °C.

$$H = H_F + \int_{298}^{Tf} C_P \times dT \quad (15)$$

Where:

H_F	Formation Enthalpy (kJ/Kmol)
T	Gas Temperature (K)
C_P	Specific Heat (kJ/KmolK)

Table 11. Enthalpy Values and Molar Mass for each element at atmospheric press.

Formation Enthalpy	Enthalpy Value (kJ/kg)	Molar Mass (kg/kmol) (*)	Gas Enthalpy (kJ/kg)
HN_2	20585,14	28,013	6865,2
HO_2	21852,24	32	
HH_2	8599,97	2,016	
HCH_4	-8245,51	16,043	
HCO	-4086,18	28,01	
HCO_2	-9150,13	44,01	
HH_2O	-13769,13	18,015	

(*) Source: Thermodynamics Fundamental, Van Wylen, SOnntag, Borgnakke, Edit 5th, 1998

$$Biomass + Air = CO_2 + H_2O + SO_2 + N_2 \quad (16)$$

The different entalphies (ΔH) represent Lower Heat Value (LHV). For biomass was considered 19040 kJ/kg (Lora and Nogueira, 2003)

$$\Delta H = -LHV = \sum_{PRODUCTS} H_F - \sum_{REAGENTS} H_F \quad (17)$$

In the other hand, formation enthalpy of Air at 250 °C is 225,27 kJ/kg (Coronado, 2006). The value of biomass enthalpy formation is -56907,29 kJ/kg, and the biomass enthalpy is -51942,92 kJ/kg. The heat losses are -252718,72 kW (SQS) and -248424,31 kW (CQS).

3.2.5.1 Gasifier Efficiency.

In thermal applications the value of cold efficiency is very important, because the gas is employed in Gas Turbine system (Lora e Nogueira, 2003).

$$EF_{COLD} = \frac{M_{GAS} \times LHV_{GAS}}{M_B \times LHV_{BIOMASS} + M_{AIR} \times H_{AIR}} \tag{18}$$

$$EF_{HOT} = \frac{M_{GAS} \times LHV_{GAS} + M_{GAS} \times H_{GAS}}{M_B \times LHV_{BIOMASS} + M_{AIR} \times H_{AIR}} \tag{19}$$

Where:

EF_{COLD}	Cold Efficiency (%)
EF_{HOT}	Hot Efficiency (%)
LHV_{GAS}	Gas Lower Calorific Heat (kJ/Nm^3)
$LHV_{BIOMASS}$	Biomass Lower Calorific Heat (kJ/Nm^3)
H_{GAS}	Gas Enthalpy (kJ/Nm^3)
$H_{BIOMASS}$	Biomass Enthalpy (kJ/kg)

Table 12. Hot Efficiency and Cold Efficiency Values.

Burning	LHV_{GAS}	$LHV_{BIOMASS}$	M_{GAS}	M_B	EF_{COLD}	H_{GAS}	$H_{BIOMASS}$	EF_{HOT}
SQS	5565,45	19400	59764,17	4,59	79,34	6865,52	-51942,92	86,37
CQS			49157,46	4,54	65,37			71,17

3.3 Economical Analysis.

In recent work (Silveira, 1990), a methodology for determinate electricity cost, and expected annual revenue, considering a fuel cost, operation cost, payback and electricity price was developed. The value of electricity price is available in ANEEL (National Agency of Electrical Energy) (http://www.aneel.gov.br/area.cfm?idArea=98&idPerfil=4). Since 2007 in rural zones the price is 174,68 R$/MWh or 0,1078 US$/kWh.

Table 13. Investments and Reparation Cost of Equipments.

Equipments	Investments (USD)		Reparation (USD/kWh)
	SQS	CQS	
Gas Turbine	7250000,00	7510320,00	0,015
HRSG	2900000,00		0,001
Steam Turbine	10000000,00		0,015
Pump	400000,00		
Gasifier	14185000,00		
Condenser	2000000,00		0,008
	SQS	CQS	0,048
Total	51429000,00	51939227,20	

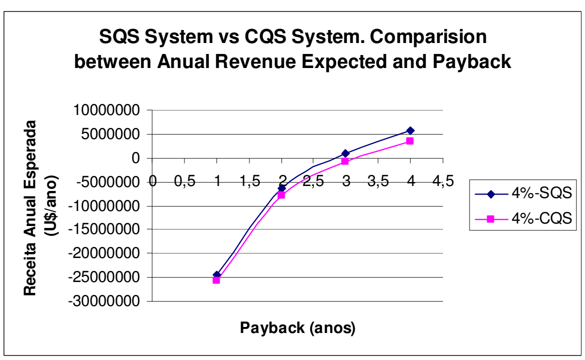

Figure 5. Comparison of the BIGCC system for interest tax of 4%

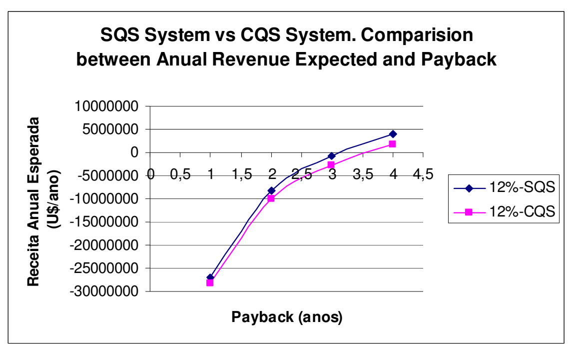

Figure 6. Comparison of the BIGCC system for interest tax of 12%.

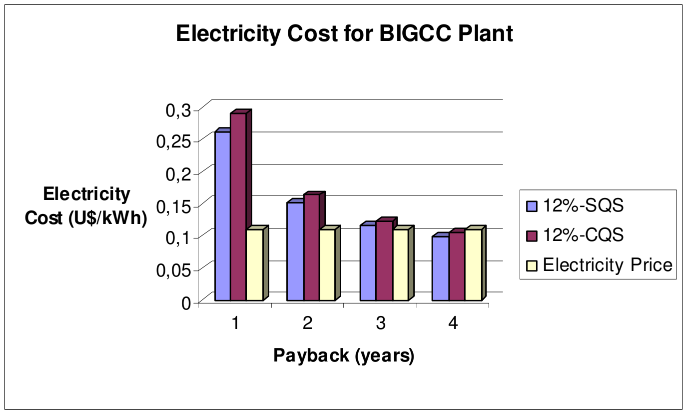

Figure 7. Comparison between Electrical Cost for SQS System and Electrical Cost for CQS System.

3. Conclusions.

In this paper the reference value of energy required for system evaluation on rural zones was 30 MW. For this condition a BIGCC represents a good option for electricity production since presents low cost of electricity production. This paper presents a technical and economical comparison between system with and without supplementary burning. In this system a technical point view represents a relevant option for BIGCC, because presents a high value of cold efficiency (79,34%), but combined cycle efficiency is low (49,29%); and in this economical point view a option SQS is better because presents a low period of amortization (32 months for interest tax of 12%) and low electrical cost. In the CQS system, occurs the contrary. In this case technical point view present a high efficiency in a combined cycle, but presents a low cold efficiency (65,37%), and economical point view a period of amortization (42 months for interest tax of 12%) and cost of electrical produce is high. Finally, for this condition the BIGG system without supplementary burning represents a good option for rural zones.

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