Technical and economical evaluation of electricity generation from biomass in a gasifier / SOFC system.

Quelbis R. Quintero B., quelbisquintero@yahoo.com
Vladimir R. Cobas M., vladimir@unifei.edu.br
Electo E. Silva L., electo@unifei.edu.br
Nucleus of excellence in thermolectric generation and distributed generation – NEST, Mechanical Engineering Institute - Federal University of Itajubá.

Abstract.

This techno-economic study examines a case of synthesis gas production from biomass gasification of Eucalyptus in various types of gasifiers: D2SG (two-stage gasifier co-current), installed at the Federal University of Itajubá; V2SPG (gasifier with Pyrolysis and gasification in two separate stages), developed at the Technical University of Denmark and FICFB (Fluidized internal circulation bed gasifier), installed in Güsing - Austria, to produce electricity in a fuel cell SOFC system with external reforming. Three scenarios were developed: in the first stage, gases are composed at the D2SG gasifier are composed of 20% CO, 1,8% CH4 and 16% H2; in the second scenario, the V2SPG gasifier gas composition is18% CO, 1% CH4, 31% H2, 15% CO2, and 35%N2; while in the third scenario the gasifier FICFB's gas is composed of 29% CO, 9% CH4, 35% H2, 16% CO2 and 3% N2. The system modeling was suitable for economic analysis, each of the scenarios demonstrating unfeasible results according to the value stipulated by ANEEL for the price of electricity from biomass equal to USD $ 88.2 / MWh, currently in place in Brazil. On the other hand, the analysis allowed the calculation of a price per kWh to generate a TIR of 16% at a capital cost of 18%, which was estimated at USD $ 405 MWh for the D2SG plant, USD $ 398 MWh for the V2SPG plant and USD $ 399 MWh for the FICFB plant, reflecting little difference between them, although the FICFB plant proved to be more efficient in processing gas, with a rate of 67.7%..

Electricity production from Eucalyptus biomass gasification coupled to a fuel cell system with external reforming is not viable from an economic point of view, in order to compete with current renewable energy prices due to high costs and further investment and availability of technical support. From a technological, environmental, social and geopolitical standpoint electricity production from eucalyptus biomass gasification would be viable if one considered an estimated electricity tariff of (U.S. $ 200/MWh).

***Keywords**: Fuel cell, hydrogen, SOFC, biomass, Eucalyptus.*

1. INTRODUCTION

Renewable fuels have recently increased their fraction in the overall energy consumption, given that an increase of 4.4% per year between 2007 and 2030 has been forecasted (EIA, 2009). By 2030, energy from biomass in primary markets is expected to reach 20% of renewable energy sources (Valverde, 2010), hence the importance of exploring new, economically viable technical alternatives -.

Systems based on biomass fuels are considered sustainable as they are practically carbon neutral. The most common technology used is to generate electricity is the burning wood to generate steam, the latter being used to power a steam turbine (Colpan *et al.*, 2009). These systems have low efficiency and high investment cost and only become viable when fuel costs are near zero. Synthesis gas can be obtained as a fuel through biomass gasification for use in fuel cells, offering a high potential for generating electricity from renewable energy with high efficiency, with not only energy benefits, but also environmental and social. Of all the existing cells, Solid Oxide Fuel Cell technology - SOFC – seems to be the most promising to take advantage of the gasified biomass, due to its high operating temperature not requiring pure hydrogen as fuel, that allows great flexibility in the fuel composition (Seitarides *et al.*, 2008), plus its high level of efficiency. Fuel cells have important advantages, including low levels of NOx, CO and HC, compared with gas turbine and engines (Walter and Horta, 2008). The production of electricity through a SOFC fuel cell using Eucalyptus biomass now shows itself to be an interesting alternative for the diversification of the global energy mix and reduction of dependence on nonrenewable energy sources.

The technical analysis of an energy solution is not sufficient to determine its feasibility, hence the importance of further comprehensive analysis, assessing social, economic, environmental, geopolitical becomes apparent to its success. The electricity generation system considered consists of a reformer, a SOFC fuel cell, a combustor and auxiliary equipment.

Through the use of software CycleTempo, the complete system was modeled for the generation of 1 MW of electricity and from the mass and energy balances, and system and biomass acquisition costs, the electricity generation costs were determined. The results allow the determination of which factors have the greatest influence on the techno-economic feasibility of such systems, considering electricity generation market prices for electricity in the range of $200 - $500 USD / MWh

This paper presents a techno-economic analysis based on a Cycle Tempo model, which integrates an SOFC fuel cell with an external reformer to crack the methane and carbon compounds present in the synthesis gas to hydrogen and achieve higher gas product efficiencies from gasification of Eucalyptus. It is estimated as paradigm for future investment in electricity generation from biomass with improved efficiencies if compared to those currently established.

2. MATERIAL AND METHODS

The analysis was conducted with the Cycle Tempo software as a tool for process simulation, which consists of the operation of the synthesis gas system with three types of gasifiers to produce electricity with an external reformer and SOFC fuel cell with a 1 MW capacity. It was necessary to provide some methods and parameters for carrying out economic analysis based on the Internal Rate of Return on Investment and a sensitivity analysis to estimate a price range of MWh cost of SOFC technology

2.1 CHARACTERISTICS OF THE GASIFIERS AND REFORMER

The D2SG plant is equipped with a fixed bed reactor type co-current two-stage gasifier, made of steel, coated with refractory material and isolated, which has an efficiency of 70%, is installed at the Brazilian Federal University of Itajubá. The V2SPG plant gasifier is a two-stage pilot plant gasification co-current type tested at the Technical University of Denmark. This unit separates pyrolysis and gasification and exhibits a reported efficiency of 93%. The FICFB plant, located in Austria, consists on a circulating bed gasifier using steam as a gasification agent. The heat energy from a separated combustion reactor is used to sustain the endothermic reaction of steam gasification and is supplied using the inert as energy. The gasifier efficiency is 85%. The reformer operates at a temperature of 800 ° C and reaches an efficiency of 75% (Wright *et al.*, 2010; Andrade *et al.*, 2010; Sosa *et al.*, 2009; Bolhàr-Nordenkampf *et al.*, 2009). The different gas compositions for the evaluated gasifiers are shown in Table 1.

Table 1. Gas composition of the test plants

Components	Elemental composition of the gas on each plant [%Vol]		
	D2SG	V2SPG	FICFB
Base	B.S	B.S	B.H
CO	20	18	29
CH_4	1,8	1	9
H_2	16	31	35
CO_2	--	15	16
N_2	--	35	3

Source: Andrade and others , 2010.

The syngas composition's variation is notable in the three different plants, as it can be noted that the content of CH4, H2 and CO is differentially higher on the FICFB plant with respect to the D2SG and V2PG, which leads to a greater electricity conversion efficiency in the SOFC system. In the same sense the N2 content in the FICFB plant is 10 times lower with respect to the V2SPG, providing more power in this gas, as only 3% in volume is an inert gas.

2.2 BIOMASS

The biomass selected for the study was Eucalyptus, due to its rapid growth, productivity, highly adaptable nature and for being present in every state in Brazil. As an assessment criterion, the estimated average yield per hectare of 50 $m^3ha^{-1}year^{-1}$ with a purchase price of 45 R $ / m^3, put on the plant. The assumed Lower Heating Value (LHV) was 18,640 kJ / kg, the specific weight of 700 kg/m^3.

2.3 THERMO PROCESS ANALYSIS

The analysis proposes an electrical energy production system for isolated regions of Brazil with high efficiency and almost inexistent greenhouse gas emissions. The system consists of an SOFC fuel cell operating with eucalyptus syngas with external reforming, whose objective is to attain the system's highgest efficiency through biomass combustion and steam turbine. The general gasifier system scheme – SOFC – is illustrated in Figure 1.

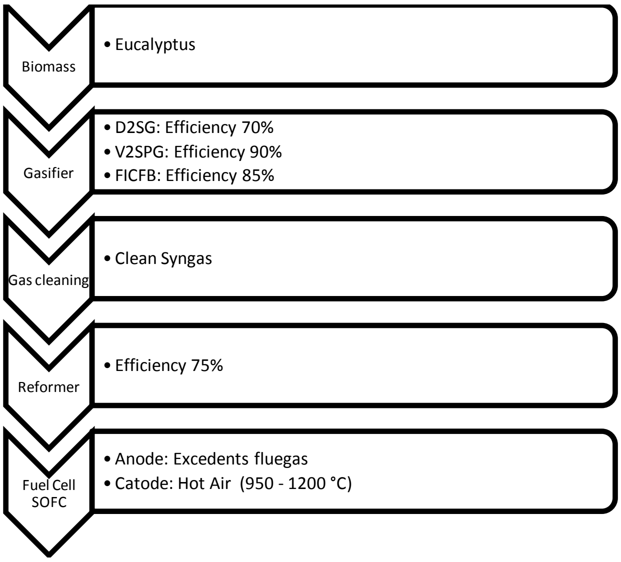


Figure 1. General scheme of the gasifier system - SOFC

The software Cycle Tempo, developed by Delft University in Holland, is used as an analysis tool. The program serves for thermodynamic modeling and optimization of electricity production systems, heating and cooling systems formed, many times, by several different devices with interconnected cycles, among which include the SOFC fuel cell. The system designed for this research, is a fuel cell with an external reformer, in order to increase efficiency. It is composed of: 1 reformer that operates at 800 ° C, 1 combustor, a fuel cell SOFC, 6 heat exchangers, 1 blower, 3 pumps, 1 compressor. and a recirculation tank. It is assumed that the gas is clean and working pressure is equal to 1 bar air and the ambient temperature is equal to 25 ° C. See Figure 3.

Having the model developed, the most important parameters used for simulation are:

- **Reformer:** Operating Temperature: 800 ° C, the allowable pressure drop is 0.05 bar and the efficiency is 75%.
- **Fuel cell:** Anode pressure of 1.15 bar, pressure at the cathode equal to 1.15 bar, the allowable pressure drop in both the anode and the cathode is 0.05 bar. Initial temperature at the anode equal to 850 ° C, initial temperature at the cathode equal to 850 ° C, final temperature of the cell is 950 ° C, 1 MW power and conversion efficiency of direct current to alternating current equal to 0.96.
- **Combustor**: The allowable pressure drop is 0.01 bar to ensure optimum performance and the reactor temperature is 1200 ° C.

2.4 THE THERMODYNAMIC MODEL

The Cycle Tempo computed mass and energy balance at each point in the cycle of the process preparing a square matrix that represents the flow, finding the values of variables for analysis. The mathematical models used in software to have continued:

Mass balance

$$\sum_{j=1}^{n_i} \phi_{m,in}(j) - \sum_{j=1}^{n_i} \phi_{m,out}(i) = b(k) \tag{1}$$

k is the number of equations

Energy balance

$$\sum_{j=1}^{n_i} \phi_{m,in}(j) \times h_{in}(j) - \sum_{j=1}^{n_i} \phi_{m,out}(i) \times h_{out}(i) = b(l) \qquad (2)$$

l is the number of equations

Where: $\phi_{m,in}$ is mass flow at the entrance; $\phi_{m,out}$ is mass flow at the out; h_{in} is enthalpy flow at the entrance; h_{out} is enthalpy flow at the out.

2.4.1 REFORMER

In the reformer equilibrium reactions take place. The equilibrium are calculated by means of equilibrium constants. These constants are a function of the temperature.

$$K_{reaction} = f(T_{reaction}) \qquad (3)$$

In which: $K_{reaction}$ is equilibrium constant (dimension depends on reaction); $T_{reaction}$ is temperature at which the equilibrium is calculated (K)

The CO shift or watergas shift reaction:

$$CO + H_2O \leftrightarrow CO_2 + H_2 \qquad (4)$$

With equation

$$KPS = \frac{(\partial p_{CO_2}+x)(\partial p_{H_2}+x)}{\left((\partial p_{CO}-x)(\partial p_{H_2O}-x)\right)} \qquad (5)$$

The CH$_4$ - reforming reaction:

$$CH_4 + H_2O \leftrightarrow CO + 3H_2 \qquad (6)$$

With equation

$$KM = \frac{(\partial p_{CO}+y)(\partial p_{H_2}+y)^3}{\left((\partial p_{CH_4}-y)(\partial p_{H_2O}-y)\right)} \qquad (7)$$

Where: ∂p_x is the partial pressure of component x; x is the reaction coordinate of the watergas shift reaction; y is the reaction coordinate of the CH_4 reforming reaction; KPS is the reaction constant of the watergas shift reaction and KM is the reaction constant of the CH$_4$ reforming reaction.

The equations 5 and 7 are polynomes x and y in the second degree and fourth respectively. The roots are calculated by iteration due to the fact that the reactions may have more room (at different temperatures) to achieve balance. Once you get the balance can get the gas composition.

2.4.2 FUEL CELL

The modeling process in the fuel cell involves three major blocks, as shown in figure 2.

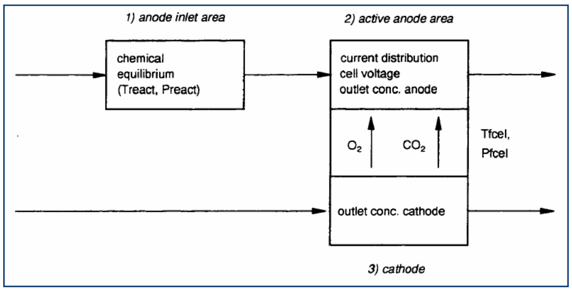


Figure 2. Framework of the model (Source: Cycle-Tempo Manual, 2005)

The equation of mass of the fuel cell is:

$$\phi_{m,a,in} + \phi_{m,c,in} - \phi_{m,a,out} + \phi_{m,c,out} = 0 \tag{8}$$

In which: ϕ_m is mass flow [kg/s]; a: anode; c: cathode

In the active zone of the anode, the different flows are calculated using the following equations. The actual flow of the fuel cell is given by:

$$I = I_F \times U_f \tag{9}$$

Where: I is current [A]; U_f: fuel utilisation [-] and F is fuel

U_f is the utilization factor of fuel used is normally a value of 0.85. The value of I_F is given,

$$I_F = \frac{\phi_{m,a,in}}{M_{mol,a}} \times \frac{\left(y^0_{H_2} + y^0_{CO} + y^0_{CH_4}\right)}{2F} \tag{10}$$

Where: M_{mol} is mole mass [kg/mole]; F is Faraday's constant [C/mole] and y_j is mole fraction component j [-]

The electrical power output of the fuel cell is obtained as follows:

$$P_e = V \times I \times \eta_{DCAC} \tag{11}$$

Where: V is cell voltage [V] and $\eta DCAC$ is efficiency of DC/AC-conversion [-]

At the cathode, the equations describing the mass transport process of the cathode to the anode is:

$$\phi_{m,O_2,c\rightarrow a} = M_{mol,O_2} \times \frac{I}{4F} \tag{12}$$

The tension in the cell is calculated with the following relationships:

$$E_x = E^0_T + \frac{RT_{cell}}{2F} ln\left\{\frac{y_{O_{2,c}}^{1/2}\, y_{H_2,a}}{y_{H_2O,a}} \times p_{cell}^{1/2}\right\} \tag{13}$$

Where: R is universal gas constant [kJ/moleK]; T is temperature [K]; p is pressure [bar]

ET^0 is the standard voltage for reversible hydrogen, which only depends on temperature and is calculated from the change in Gibbs energy, ΔG:

$$E^0_T = +\frac{\Delta G^0_T}{2F} \tag{14}$$

In which ΔG is change in Gibbs energy [kJ/mole].

The voltage value taking into account the irreversibility was achieved with the following equation:

$$V = E_x - \Delta V_x \tag{15}$$

Where: E is reversible voltage [V] and ΔV is voltage loss [V].

2.4.3 COMBUSTOR

The different calculations and relationships that are used in combustor model are:

The calculations started with the determination of the fraction of oxidizer from the combustion gas temperature using the energy equation, thus:

$$h_{ox}(T_{ox}) \times OF + h_{fu}(T_{fu}) = h_{fg}(T_{fg}) \times (1 + OF) + h_{as}(T_{as}) \times AF - Q_{loss} \tag{16}$$

We have:

$$OF = \lambda \times OF_{st} \tag{17}$$

$$OF_{st} = \frac{\sum_{fuel}(\upsilon_{C,n} + {}^{1}/_{2}\upsilon_{H,n} - \upsilon_{O,n})}{\sum_{oxid}(\upsilon_{C,n} + {}^{1}/_{2}\upsilon_{H,n} - \upsilon_{O,n})} \tag{18}$$

The temperature of the combustion gases can be calculated with the equation of energy on the incinerator, thus:

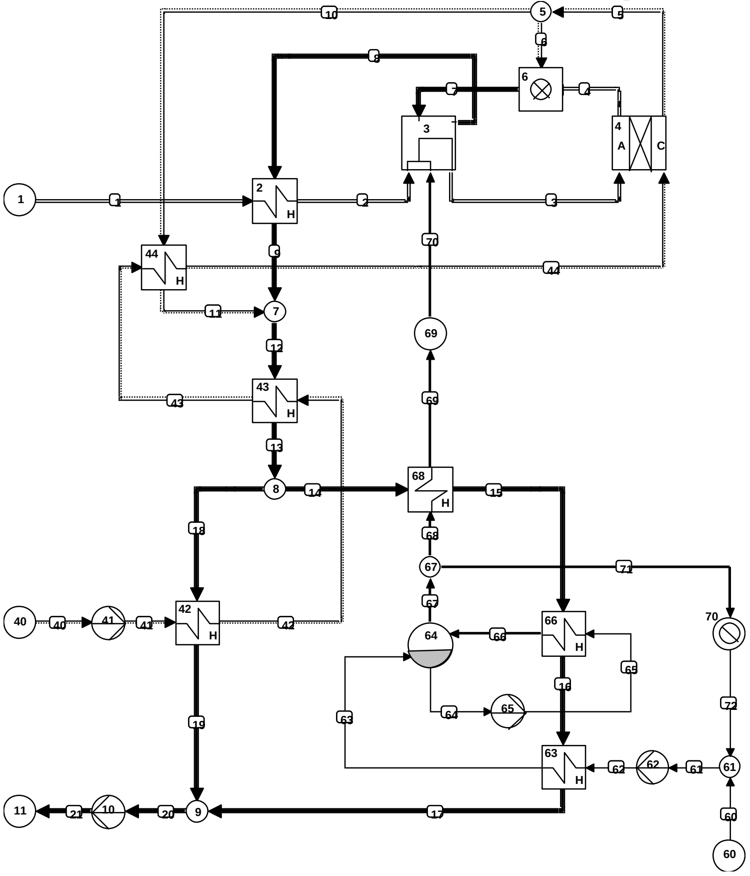
$$\phi_{m,fg} \times h_{fg}\left({T_{fg}}^{i}\right) = \phi_{m,ox} \times h_{ox} + \phi_{m,fu} \times h_{fu} - \phi_{m,as} \times h_{as}\left({T_{fg}}^{(i-1)}\right) - Q_{loss} \tag{21}$$

Where: h_{fg} is enthalpy of the mixture of flue gas; OF_{st} is oxidant/fuel ratio; $\nu_{H,n}$ is number H atoms in component n; $\nu_{C,n}$ is number C atoms in component n and $\nu_{O,n}$ is number O atoms in component n.

2.5 INVESTMENT ANALYSIS

For economic analysis, some indicators are assumed which are currently needed to calculate the Internal Rate of Return – IRR – based on Brazil Brazilian economic conditions. The electricity market price is equal to 88.2 *USD/Mwh* with a discount rate of 18%. A sensitivity analysis was performed to estimate the cost per MWh in function of the SOFC technology's cost, which varies in the analysis from 5000 - 500 USD / kW for the three plants, thus enabling the generation cost per MWh for an IRR of 16% at a discounted rate of 18%.

The cost of a fuel cell of 1 MW was estimated, taking into account the reported costs by Pehnt and Ramesoohl (2003), whose value are around 5000 *USD / kW*. The system's construction costs were estimated in function of the cost of equipment, using factors established on the basis of conventional generation technologies, based on the recommendation of the Association for the Advancement of Cost Engineering (AACE). In doing so, reasonable results are obtained in the conceptualization of the cost of electrical power systems, fuel cells and turbines (EG&G, 2004) and are applicable to processes that operate at temperatures above 200 °C and pressures below 150 psi, and were taken AACE 16R Standard, Evaluation Economic and technical processes of industry and public service.



Apparatus

2. Heat Exchanger
3. Reformer
4. Fuel Cell
6. Combustor
10. Pump
41. Blower
42. Heat Exchanger
43. Heat Exchanger
44. Heat Exchanger
62. Pump
63. Heat Exchanger
64 Drum
65. Pump
66. Heat Exchanger
68. Heat Exchanger
70. Steam Net

Figure 3. Model of the Solid Oxide Fuel Cell (SOFC) system with external reforming and bypass

The estimated investment costs according to current prices are listed in Table 2, taking into consideration the technology at each plant and auxiliary equipment.

Table 2 Estimated investment cost

Description	D2SG	V2SPG	FICFB
Fuel Cell	USD 5.000.000,00	USD 5.000.000,00	USD 5.000.000,00
Gasifier	USD 350.000,00	USD 350.000,00	USD 385.000,00
Heat Exchangers	USD 150.000,00	USD 180.000,00	USD 250.000,00
Computer and Telecommunications	USD 8.750,00	USD 8.750,00	USD 8.750,00
Furniture	USD 6.000,00	USD 6.000,00	USD 6.000,00
Physical plant and auxiliary equipment	USD 5.035.500,00	USD 6.156.500,00	USD 6.156.519,25
Land	USD 12.000,00	USD 12.000,00	USD 12.000,00
Deferred Assets	USD 115.400,00	USD 115.400,00	USD 115.400,00
Total Investment	USD 11.796.650,00	USD 11.828.650,00	USD 11.933.669,25

2.5 RESULTS AND DISCUSSION

The simulated process begins with the outlet of gas from the cleaning system at a temperature of 550 º C and its entry into a heat exchanger to raise its temperature to 850 ° C and subsequent entry in the reformer between 800 - 850 ° C, where steam cracking occurs at 400 ° C. The next step is it inlet to the anode of the SOFC fuel cell, to for conversion into electrical energy with a 75% utilization coefficient of this gas, while the hot air enters the cathode at a temperature of 850 ° C. The excess gas which does not react in the cell where the temperature is 1100 ° C is used as fuel for the combustor which in turn delivers that transformed energy after reacting with a fraction of the air at 1010 ° C, leaving the anode cell and going to the reformer. The remaining fraction of air is used in heat exchangers and raises the temperature of the air entering the system. The system has other ancillary equipment (pumps and blower), as well as heat exchangers, that are taken into account in calculating the system's efficiency. The system also requires water at a rate of 0.223 kg / s for steam production. The flow of cold air entering the system is 4.634 kg / s.

The results of the main operating parameters of the fuel cell using syngas from different types of gasifiers are presented in Table 3. These data were compared with data presented by Malkow (2008) to corroborate their validity

Table 3. Some parameters of the fuel cell coupled to the evaluated type of of gasifiers

Gasifier Type	**Power** ***(MW-CA)***	**Current Density** ***(A/m2)***	**Analyzed System**		**Malkow (2008)**	
			Voltage ***(V)***	**Power density** ***(kW/m²)***	**Voltage (V)**	**Power Density (kW/m2)**
D2SG	1,00	2.509,76	0,59	1,49	0,66	1,65
V2SPG	1,00	2.415,54	0,62	1,49	0,67	1,64
FICFB	1,00	2.257,80	0,66	1,49	0,69	1,57

The model's percentage deviations with respect to the results obtained by Malkow (2008), in terms of voltage versus current density range between 10.6% and 4.4%, showed themselves to be lowest in the plant FICFB and largest in the plant D2SG. In the same sense, for the power density, such deviations ranged between 9.7% and 5.1% and were distributed in the same way as in the case of the voltage. Accordingly, it can be concluded that the data are consistent to present percentage deviations between 4% and 10% and can be considered acceptable. It can be argued that the purpose of this deviation could be due to the fuel utilization ratio, which for this study used 0.75 and 0.85.

According to the results of the model for the SOFC fuel cell system with external reforming, which seem to be within acceptable ranges, an analysis of overall system efficiency and the respective necessity estimates for Eucalyptus biomass, costs and IRR were carried out.

2.5.1 SIMULATION RESULTS

The results shown in table 4 are the values calculated by the software cycle tempo for each flow cycle analysis for the different synthesis gases.

Tabla 4. Properties of flows in cycles analyzed for each synthesis gas

Pipe No.	D2SG					V2SPG					FICFB				
	Mass Flow [kg/s]	Mole Flow [kmol/s]	Pressure [bar]	Temp. [°C]	Enthalpy [kJ/kg]	Mass Flow [kg/s]	Mole Flow [kmol/s]	Pressure [bar]	Temp. [°C]	Enthalpy [kJ/kg]	Mass Flow [kg/s]	Mole Flow [kmol/s]	Pressure [bar]	Temp. [°C]	Enthalpy [kJ/kg]
1	0.7316	0.0281	1.00	550	2508.59	0.4901	0.0220	1.00	550	-2817.84	0.2227	0.0109	1.00	550	-4109.75
2	0.7316	0.0281	0.98	900	2020.96	0.4901	0.0220	0.98	900	-2257.45	0.2227	0.0109	0.98	900	-3442.72
3	1.4633	0.0697	1.15	850	-6906.60	0.9802	0.0497	1.15	850	-7040.87	0.4454	0.0252	1.15	850	-7225.29
4	1.6098	0.0697	1.10	1010	-7341.71	1.1204	0.0497	1.10	1010	-7730.68	0.5765	0.0252	1.10	1010	-8719.75
5	4.0500	0.1409	1.10	1010	994.08	4.3111	0.1499	1.10	1010	994.17	4.5032	0.1565	1.10	1010	994.27
6	0.4797	0.0167	1.10	1010	994.08	0.4757	0.0159	1.10	1010	994.17	0.4206	0.0146	1.10	1010	994.27
7	2.0887	0.0849	1.09	1221	-5247.07	1.5762	0.0641	1.09	1279	-5207.86	0.9971	0.0285	1.09	1427	-4622.19
8	2.0887	0.0849	1.04	1043	-5742.57	1.5762	0.0641	1.04	1128	-5477.97	0.9971	0.0285	1.04	1212	-4994.13
9	2.0887	0.0849	1.02	944	-5913.38	1.5762	0.0641	1.02	1028	-5652.22	0.9971	0.0285	1.02	1124	-5142.14
10	3.5702	0.1242	1.10	1010	994.08	3.8553	0.1340	1.10	1010	994.17	4.0826	0.1419	1.10	1010	994.27
11	3.5702	0.1242	1.09	750	688.50	3.8553	0.1340	1.09	760	688.66	4.0826	0.1419	1.09	750	688.81
12	5.6589	0.2091	1.02	839	-1748.21	5.4315	0.1981	1.02	854	-1151.41	5.0797	0.1804	1.02	846	-455.92
13	5.6589	0.2091	1.00	673	-1970.52	5.4315	0.1981	1.00	667	-1393.38	5.0797	0.1804	1.00	630	-721.19
14	3.7686	0.1392	1.00	673	-1970.52	3.3499	0.1222	1.00	667	-1393.38	2.6525	0.0942	1.00	6305	-721.19
15	3.7686	0.1392	0.99	600	-2065.06	3.3499	0.1222	0.99	611	-1464.63	2.6525	0.0942	0.99	596	-762.09
16	3.7686	0.1392	0.94	201	-2554.68	3.3499	0.1222	0.94	201	-1954.61	2.6525	0.0942	0.94	201	-1213.29
17	3.7686	0.1392	0.93	81	-2692.62	3.3499	0.1222	0.93	78.85	-2091.66	2.6525	0.0942	0.92	55	-1228.42
18	1.8902	0.0698	1.00	673	-1970.52	2.0815	0.07593	1.00	667	-1393.38	2.4271	0.0862	1.00	630	-721.19
19	1.8902	0.0698	0.98	80	-2693.99	2.0815	0.0759	0.98	80	-2090.39	2.4271	0.0862	0.98	50	-1343.53
20	5.6589	0.2091	0.93	81	-2693.07	5.4315	0.1981	0.93	79	-2091.17	5.0797	0.1804	0.93	83	-1340.87
21	5.6589	0.2091	1.01	91	-2681.33	5.4315	0.1981	1.01	90	-2079.62	5.0797	0.1804	1.01	93	-1329.51
40	4.1956	0.1454	1.01	15	-98.85	4.4513	0.1543	1.01	15	-98.85	4.6342	0.1606	1.01	15	-98.85
41	4.1956	0.1454	1.20	34	-79.64	4.4513	0.1543	1.20	34	-79.64	4.6342	0.1606	1.20	34	-79.64
42	4.1965	0.1454	1.18	350	246.31	4.4513	0.1543	1.18	350	246.31	4.6342	0.1606	1.18	350	246.31
43	4.1965	0.1454	1.16	624	546.15	4.4513	0.1543	1.16	620	541.66	4.6342	0.1606	1.16	616	537.08
44	4.1965	0.1454	1.15	850	806.18	4.4513	0.1543	1.15	850	806.19	4.6342	0.1606	1.15	850	806,18
60	0.73163	0.0406	1.20	20	84.03	0.4901	0.0272	1.20	20	84.03	0.2227	0.0124	1.20	20	84.03
61	0.88031	0.0487	1.00	21	87.56	0.7831	0.0435	1.00	22	91.85	0.5710	0.0317	1.00	23	96.78
64	0.88031	0.0487	10.40	21	88.67	0.7831	0.0435	10.40	22	92.96	0.5710	0.0317	10.4	23	97.89
63	0.88031	0.0487	10.20	161	679.20	0.7831	0.0435	10.20	161	679.20	0.5710	0.0317	10.2	160	679.20
64	9.18510	0.5098	10.20	181	766.49	8.1712	0.4536	10.20	181	766.49	5.9581	0.3307	10.2	181	766.49
65	9.18510	0.5098	11.70	181	766.72	8.1712	0.4536	11.70	181	766.72	5.9581	0.3307	11.7	181	766.72
66	9.18510	0.5098	10.20	181	967.63	8.1712	0.4536	10.20	181	967.63	5.9581	0.3307	10.2	181	967.62
67	0.88031	0.0489	10.20	181	2777.87	0.7831	0.0435	10.20	181	2777.87	0.5710	0.0217	10.2	181	2777.87
68	0.73163	0.0406	10.20	181	2777.87	0.4901	0.0272	10.20	181	2777.87	0.2227	0.0123	10.2	181	2777.87
69	0.73163	0.0406	9.70	400	3264.86	0.4901	0.0272	9.70	400	3264.86	0.2227	0.0123	9.70	400	3264.86
70	0.73163	0.0406	9.70	400	-12706.65	0.4901	0.0272	9.70	400	-12706.68	0.2227	0.0123	9.70	400	-12706.65
71	0.14868	0.0083	10.20	181	2777.87	0.2930	0.0163	10.20	181	2777.87	0.3483	0.0193	10.20	181	2777.87
72	0.14868	0.0083	1.00	25	104.93	0.2930	0.0163	1.00	25	104.93	0.3483	0.0193	1.00	25	104.92

2.5.2 SYSTEM EFFICIENCY

A determining factor in the system’s efficiency is the gas’s thermal potential, which has a direct impact on the amount of biomass needed to operate a power plant using eucalyptus. The thermal power was calculated for each plant from the LHV and mass flow estimated with the Cycle Tempo for each case. See Table 5.

The gas composition in Table 1 is consistent with the LHV calculated by Cycle Tempo and the data reported by Andrade *et al.* (2010), whose values are 5 MJ / kg for the plant D2SG and 12 MJ / kg for the plant FICFB, thus greater efficiency can be expected for the FICFB plant, and less efficiency for the D2SG plant. This is attributable to the composition of the gas and the methane content, which is higher for FICFB, providing greater thermal power after steam reforming.

Table 5. Calculation of Eucalyptus needed to produce 1 MW SOFC fuel cell with external reforming.

Gasifier Type	**LHV (gas) (kJ/kg)**	**Mass Flow (kg/s)**	**Thermal Power (kW)**	**PCI Eucalyptus (kJ/Kg)**	**Specific Weight (Kg/m3)**	**Biomass consumption (Kg/s)**
D2SG	4.214,48	0,73	3.085,00	18.640,00	700,00	0,24
V2SPG	6.023,98	0,49	2.951,75	18.640,00	700,00	0,18
FICFB	11.714,15	0,22	2.612,26	18.640,00	700,00	0,16
Gasifier Type	**Biomass consumption *(m^3/hora)***	**Biomass consumption *(m^3/dia)***	**Biomass consumption *(m^3/día/kW)***	**Biomass consumption *(m^3/kW/mes)***	**Required Area (Ha/ day)**	**Differential area (annual)**
D2SG	1,22	29,18	0,029	0,88	0,58	63,60
V2SPG	0,90	21,72	0,022	0,65	0,43	53,75
FICFB	0,85	20,35	0,020	0,61	0,41	

It is apparent from Table 5 that higher value LHV gas to requires less Eucalyptus biomass, which is reflected in the differential area that is required per year with respect to the FICFB plant, which amounts to 63.6 and 9.84 hectares for the plant V2SPG and D2SG respectively; this in turn directly affects the system's efficiency, profitability and cost of kW.

System efficiency is analyzed from the entrance of the syngas produced by each plant previous heating to the reformer, it components are different due to the utilization of different oxidizing agent in the gasification with of process in each of them. Gasifier efficiency is not considered in Table 6. and it is assumed that the gas enters free of impurities to initiate the methane cracking.

Tabla 6. Efficiency of the SOFC operating with syngas

Description	**No.**	**Apparatus**	D2SG		V2SPG		FICFB	
			Energy *[kW]*	**Total *[kW]***	**Energy *[kW]***	**Total *[kW]***	**Energy *[kW]***	**Total *[kW]***
Power								
Power absorbed	1	Fuel	3083,44	**3083,44**	2952,00	**2952,00**	2609,80	**2609,80**
Power Delivered	4	SOFC	1000,00	**1000,00**	1000,00	**1000,00**	1000,00	**1000,00**
Auxiliary Power Consumed	10	Fg. Compr	74,12		70,26		64,96	
	41	Air Compr	88,53		93,42		96,89	
	62	Whb. Fdpmp	1,63		1,45		1,05	
	65	Whb. C. Pump.	2,80		2,57		2,07	
Total Auxiliary Power				**167,08**		**167,70**		**164,97**
Net Power Delivered				**832,92**		**832,30**		**835,03**
Delivered Heat Power	70	Vapor	397,40	**397,40**	783,24	**783,24**	931,01	**931,01**
Total Delivered Power				**1230,32**		**1615,54**		**1766,04**
Efficiencies	Gross		**32,43%**		**33,88%**		**38,32%**	
	Net		**27,01%**		**28,19%**		**32,00%**	
	Heat		**12,89%**		**26,53%**		**35,67%**	
	Total		**39,90%**		**54,73%**		**67,67%**	

It can be seen in Table 5 that the most efficient system is the FICFB/SOFC, with 67.67% and the least efficient is the D2SG/SOFC Plant with 39.90%. Another important factor noted in accordance with these data is that the oxidizing agent used in the gasification process, determines the LHV and the loss of biomass thermal power with respect to the gas obtained. In the case of FICFB it is the steam and for D2SG it is the air and efficiencies which make the difference.

2.6 TECHNICAL AND ECONOMIC ANALYSIS

This analysis should be understood as an applied scientific analysis and technical assessment – which do not ignore the economic system, the technological components, environmental, ecological, social, strategic or geopolitical and financial implications (Fagundes *et al.*, 2008).

The investment cost and generation cost for each scenario were estimated by finding the cost of construction and operation of plants for 20 years producing 8585 MWh / year. The total capital investment was evaluated by determining the cost and installation of equipment and the addition of indirect costs. The annual operation costs were determined and a cash flow discounting from the sale of electricity in MWh, the present value of the investment at a discount rate of 18% annually, was developed.

According to the criteria defined and calculations needed for the analysis, the base value of the electricity tariff for calculating the project's revenues from commercialization electricity, is $ 88.2 / MWh, as required by ANEEL for renewable energy generation projects in Brazil and thus obtain the TIR for each gasifier type. The Net Present Value criterion is that if: NPV <0, the investments are unviable and will not generate return on investment during the evaluation period, and if NPV> 0 the investment is generating viable return on investment and if NPV = 0, the criterion is indifferent and doesn’t show return on investment. The development of the calculations yielded the results shown in Table 7.

Table 7. Results of technical and economic analysis (Exchange rate R$1,7)

Gasifier Type	**Investment (USD)**	**Cost (USD/kWh)**	**NPV (USD)**
D2SG	11,796,650	0,09	-13,501,291
V2SPG	11’828,650	0,09	-13’094’213
FICFB	11.933.669,25	0,09	-13’720’979

It can be seen that the variation of NPV is not significant, although the influence of the cost of biomass is important and administrative costs and technology are equally influential in the overall system cost. According to the criteria for the definition of viability of this project is not viable to have a NPV <0 and IRR values would be negative in the period of analysis.

Calculations are made per MWh price with Eucalyptus in a SOFC fuel cell with external reform at a discount rate equal to 18% considered to be acceptable, IRR equal biomass to 16% on a project horizon of 20 years, and are shown in Table 8.

Table 8. Electricity tariff in USD / MWh desirable for each type of system with an IRR of 16%
(Exchange rate R$1,7)

Gasifier Type	**USD/MWh**
D2SG	405
V2SPG	398
FICFB	399

According to Table 8, it is clear that the price variation with respect to the types of plants studied is not significant, but indeed is significant with respect to the value currently set by ANEEL for electricity production from renewable biomass. The ratio of the prices calculated from the current set is 4.5 times higher on average for the different plants and may be attributable to the current cost of SOFC technology.

2.7 SENSITIVITY ANALYSIS FOR TECHNOLOGY INVESTMENT COSTS AND ELECTRICITY MARKET PRICE (USD/kWh)

This analysis is valid as a reference to the influence of SOFC technology costs on prices per MWh in the plants studied. It is shown in Figure 4 that the variation is linear due to the methodology used to calculate construction costs of the plant, which is directly dependent on the costs of fuel cell and auxiliary equipment.

Note that at the current costs of SOFC technology, which are in the order of 5000 USD / kW, for a discounted rate of 18% and an expected IRR of 16%, the price of renewable MWh produced is estimated at 500 USD / MWh as the cost of SOFC technology decreases, reaching values of 500 USD / kW, the price of renewable MWh produced is estimated at 200 USD / MWh. It is important to emphasize that the influence on renewable MWh prices is not due solely to technology, but also administrative costs, technical support and the actual eucalyptus production.

As such, the environmental, social and geopolitical aspects should be determinants in the selection of these technologies for renewable electricity production, seeing that it is less pollutant and causes less environmental impact than current forms of energy production, mainly due to the extremely low emission of greenhouse gases, minimization of land use conflicts, and carbon capture, diversification of production and local climate regulation through forest production.

The selection of the type of gasifier, from an environmental point of view, would be the FICFB gasifier, due to its lower biomass consumption, thus implying less land use conflicts, fewer natural and economic resources consumed in production, although it is the greatest investment by the type of technology.

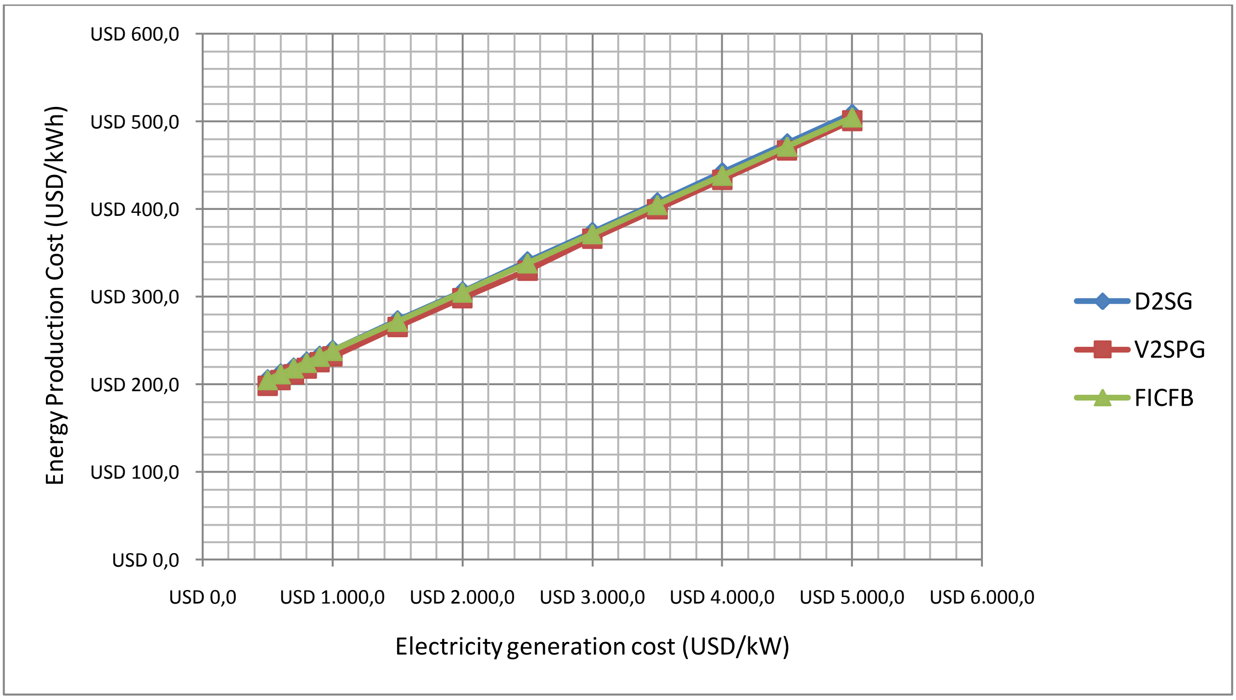


Figure 4. SOFC technology cost influences the price of produced electricity
Influencia de los costos de la tecnología SOFC en los precios de la electricidad producida.

3. CONCLUSIONS

Electricity production from Eucalyptus in a Fuel Cell system with external reforming is not get a viable from an economic point of view in order to compete with current prices for renewable energy due to high investment costs. From an environmental, social and geopolitical standpoint it would be viable if one considers a price of 200 USD / MWh. It is notable that the cost of SOFC technology is still high for the production of renewable electricity and competes with existing technologies, it is therefore necessary to decrease the cost SOFC technology to reach 500 USD / kW; as for costs greater than this, it is very disadvantageous to compete on price. It would be interesting to perform a calculation of environmental costs where the environmental services of natural resources are considered in other forms of electricity production and analysis of both these resources are committed in the context of sustainable development.

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4. REFERENCES

EIA, 2009. Energy Information Administration. Annual energy outlook 2009 with projections to 2030. 6 Jan. 2011. <http://www.eia.doe.gov/oiaf/aeo/demand.html>.

Colpan, C., Hamdullahpur, F. and others, 2009. Effect of gasification agent on the performance of solid oxide fuel cell and biomass gasification systems. International journal of hydrogen energy, Vol. 35, pp. 5001–500 9.

Seitarides, Th., Athanasiou, C. and Zabaniotou, A., 2008. Modular biomass gasification-based solid oxide fuel cells (SOFC) for sustainable development. Renewable and Sustainable Energy Reviews, Vol. 12, pp. 1251–1276.

Walter, A. and Horta N., L. A., 2008. Sistemas de produção de eletricidade a partir de Biomassa para energia. Editora Unicamp. Campinas,. Brasil. P. 573 - 607.

EG&G Technical Services, Inc., 2004. Fuel Cell Handbook, Seventh Edition. U.S. Department of Energy, Office of Fossil Energy and National Energy Technology Laboratory. USA, 427 p.

Malkow, Thomas, 2008. SOFC in brief. Modeling Solid Oxide Fuel Cells: Methods, Procedures and Techniques. Edited for Bove, R and Ubertini, S. Springer Science+Business Media, B.V. United State of American, pp 3 - 12

Pehnt, Martin and Ramesohl, Stephan, 2003. Fuel cells distribuited power: benefits, barriers an perspectives, WWF in co-operation with Fuel Cell Europe. USA, 6 Jan. 2011, <www.assets.panda.org/downloads/stationaryfuelcellsreport.pdf >

Valverde, Sebastião R., 2010. Plantações de Eucalipto no Brasil. 18 Feb. 2011. <http://www.integracaomadeiras.com.br/noticia.php?id=11>.

Wright, Mark M., Daugaard Daren E. and others, 2010. Techno-economic analysis of biomass fast pyrolysis to transportation fuels, Fuel 89. S2–S10

Andrade V., Rubenildo, Lesme J., René and Silva L., Electo, 2010,. Análise de um gaseificador de leito fixo com duplo estágio acoplado um motor de combustão interna de ignição por centelha para conversão de biomassa em energia elétrica. VI National Congress of Mecanical Engineering – 2010. Paraiba – Brasil.

Sosa, Maria I. and Luz S., José, 2009. ANÁLISIS EXERGÉTICO DE UN REFORMADOR A VAPOR DE GAS NATURAL. REVISTA CIÊNCIAS EXATAS – Universidade de Taubaté (UNITAU) – BRASIL – VOL. 15, N. 1.

M. Bolhàr-Nordenkampf, R. Rauch, K. Bosch, C. Aichernig, and H. Hofbauer, 2009. Biomass CHP Plant Güssing – Using Gasification for Power Generation, 25 Jan. 2011. <http://members.aon.at/biomasse/thailand.pdf>.

Biomass Gasification Group, DTU. The VikingGasifier. 25 Jan. 2011. <www.bgg.mek.dtu.dk>.

Fagundes B., Eduardo J., Rendeiro Gonçalo, Martins N., Manoel F. and other, 2008. Combustão e Gasificação de Biomassa Sólida: Soluções Energéticas para a Amazônia. Brasília : Ministério de Minas e Energia.

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