BIG - GT AND CEST TECHNOLOGIES FOR SUGAR CANE MILL. THERMODYNAMIC AND ECONOMIC ASSESSMENTS

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Abstract. *In this paper the results of thermodynamic and economic calculations of an integrated power plant using the Condensing Extraction Steam Turbine (CEST) and the Biomass Integrated Gasifier Gas Turbine (BIG GT) technologies are presented. A sugar mill of 205 tons of cane per hours milling capacity is considered. Although better financial results under the present economical conditions are obtained for CEST technology, best operating results could be obtained for pressurised BIG GT power plant.*

Key-words: *BIG-GT, CEST, cogeneration, sugar industry.*

1. INTRODUCTION

A considerable amount of electricity available for the national grid can be obtained using high efficiency energy conversion technologies in the sugar cane industry. For this purpose the Biomass Integrated Gasifier Gas Turbine Technology (BIG GT) introduction in sugar mills with a low steam consumption process is very attractive. The BIG GT technology is being tested in a few demonstration projects around the world.

On the other hand, steam cycles with high steam parameters (6.0-8.0 MPa and 400-500 ^{o}C) and using condensing/extraction steam turbines have been introduced in the Hawaii's sugar industry, showing a greater surplus electricity generation potential than traditional energy configurations with back pressure steam turbine and reduction valve.

A typical sugar mill has an steam consumption of 550 kg per ton of crushed cane, with 20 kWh/tc of surplus electricity generation. In modern mills these indicators are 350 kg/tc and 50 kWh/tc respectively. On a world level this efficiency could represent 50 TWh of electricity generation (Kinoshita, 1991). In Hawaii and Mauricio Islands programs for the increasing of the electricity generation from sugarcane had been suscefully developed. Hawaiian sugar mills generate an average of 60 kWh/tc, and some of them 100 kWh/tc or more. The implementation of a modernisation program which has increased the steam parameters in the sugar mills cogeneration plants up to 50 bars and 400 ^{o}C has attained to reach the mentioned levels of electricity generation (Kinoshita, 1991).

Hobson and Dixon (1998) carried out a study about the possibility of BIG GT systems implementation in Australian sugar mills conditions. The main conclusions were:

- For an specific steam consumption value of 520 kg/tc (52 % of steam in cane) the gas turbine exhaust gases energy in not enough for the process steam supply. For this steam consumption level 70 % of bagasse must be by-passed from the gasifier and fed directly to the steam generators. Even in this case the quantity of electricity produced is 230-250 times greater than for a conventional steam cycle.
- The reduction of the steam consumption from 520 kg/tc to 400 kg/tc, increases the BIG GT system available power from 88 to 148 MW. A further reduction in steam consumption up to 320 kg/tc lead to a moderate power increase to 153 MW. In the same range of analysed values a conventional steam system increases the available power from 37 to 43 MW.
- The annual generation efficiency using the BIG GT technology and considering trash utilisation (37 %) is almost four times greater than that better presently available technology.

Turn (1998) presented the results of a study considering the integration of a BIG/GT system to the Okelele Sugar Company mill with a crushing capacity of 120 tc/h and a steam consumption of 420 kg/tc. The gas turbine net power is 18.8 MWe and 4.5 MWe corresponds to the "bottoming" 41 bars pressure steam cycle. After harvest period the BIG/GT system operates as a 25.4 MWe thermal plant with a 28.5 % efficiency by using an auxiliary fuel.

Another study considered the utilisation of steam injected gas turbines (STIG type) was carried out using technical data of the Jamaican sugar mill Monimusk (Larson et al., 1987). As a result a surplus electricity production potential of 220 kWh/tc was obtained, with a steam consumption reduction up to 300 kg/tc.

A comparative study of different cogeneration options for the sugar industry was also carried out by Walter (1994).

The objective of this paper is to present the technoeconomical analysis of the BIG/GT technologies implementation in a medium capacity sugar mill, considering a technically possible reduction in steam consumption and the real power developed by the gas turbine in off-design operation with low calorific value gas.

1.1 Gasifier model.

For the BIG/GT cycles thermodynamic calculations the gas composition after gasification is taken from the results of the simulation of a bagasse pressurised gasifier using a simulation program developed for fluidised bed boilers and gasifiers operating with coal. After improvements, it has been validated for biomass gasification (Souza-Santos, 1994, 1997).

1.2 Gas turbine model.

The gas turbine engine, for the power plant herein, selected from the Turbomachinery Handbook, 1997 , was the GT10 manufactured by European Gas Turbines.

The design and off-design performance of the gas turbine engine were simulated with the TURGAS scheme, a computer program system developed by Barros (1998), which can simulate single and two shaft open cycle gas turbines.

The program links a series of thermodynamics subroutines, each representing a different engine component such as compressor, combustion chamber or turbine. Each subroutine takes specific input data and results from previous subroutines to calculate output data. So that, the program calculates the full range of engine performance parameters both for design point and, using simultaneous iteration techniques to calculate residual errors, for off-design performance.

In addition to it, the program can compute the performance with standard fuel and/or lower calorific value fuel as gasified biomass and the gas turbine engine could be the commercial or hypothetical ones designed for standard fuel and operating with lower calorific value fuel.

The analysis of the engine off-design performance was done for the power output specific fuel consumption, constant pressure specific heat and the exhaust temperature at the engine outlet, varying the engine off-design power output for the input data.

2 THERMODYNAMIC CALCULATIONS

The thermodynamics calculation input data parameters are shown in Table 1 for main mill process and several considerations. For the CEST and BIG GT technologies cases calculation assumptions are given in Tables 2 and 3, respectively. In both cases, operating thermodynamic parameters and thermal efficiencies are given only for main equipment.

Table 1. Sugar mill process data

Parameter	Unit	Value
Mill capacity	tc/h	205
Steam consumption in process[a]	kg of steam /tc	250
Power consumption [b]	kWh/tc	30 - 35

a) Source: (Larson, Odgen, Williams and Hylton, 1990).
b) Source: (Gabra and Kjellström, 1995).

Table 2. CEST technology thermodynamic calculations assumptions

Parameter	Unit	Value
Superheated steam pressure	MPa	8
Superheated steam temperature	°C	500
Process steam pressure	MPa	0.3
Process steam temperature	°C	137
Exhaust steam pressure	MPa	0.07
Exhaust steam temperature	°C	39
Net boiler efficiency	%	80
Steam turbine nominal power	MW	20
Steam turbine efficiency	%	80
Electric generator efficiency	%	98
Continuous leakage in boiler	% total flow	3

Table 3. Assumptions for thermodynamic calculations for BIG GT technology.

Parameter	Unit	Value
Air fuel ratio in to the gasifier[a]	$kg_{air}/kg_{bag.}$	0.933
Gas fuel ratio in to the gasifier[a]	$kg_{gas}/kg_{bag.}$	1.78
Outlet gasifier temperature[a]	°C	808
Inlet wet of bagasse to the gasifier[a]	%	20
Operating gasifier pressure	MPa	0.22
Clean syngas volumetric composition[a]:		
(H_2)	%	7.41
(CO)	%	8.57
(CO_2)	%	20.40
(CH_x)	%	9.21
(H_2O)	%	3.21
(N_2)	%	51.20
Lower Heating Value	kJ/kg	4486.7
Technical data for ABB-GT10 turbine[b]:		
Fuel temperature in combustion chamber	°C	450
Temperature Inlet Turbine (TIT)[c]	°C	1167
Pressure ratio[c]	-	14
Compression maximum efficiency	%	92
Combustion chamber efficiency	%	99.6
Expander mechanical efficiency	%	97
Electric generator efficiency	%	98.5
Mechanical power with natural gas[c]	MW	24.6
Technical data for steam turbine:		
Back pressure turbine	-	-
Nominal power	MW	6.5
Total efficiency	%	74.5
Electric generator efficiency	%	98
Steam pressure, boiler out	MPa	8
Steam pressure to process	MPa	2.5
Steam temperature to process	°C	137
HRSG data as is refereed by (B&W, 1992) for single pressure level boiler.		
Ambient temperature	°C	25
Ambient pressure	MPa	0.1

a) Source (Souza Santos, 1997).
b) The steam turbines thermodynamic calculations were carried out using the TURGAS.
c) Source (International TurboMachinery Handbook, 1997).

2.1 Thermodynamic calculations results (CEST technology).

The results of thermodynamic calculations for the CEST technology and integrated to the sugar mill process are shown in Figure 1, that also shows the main mass and energy flows.

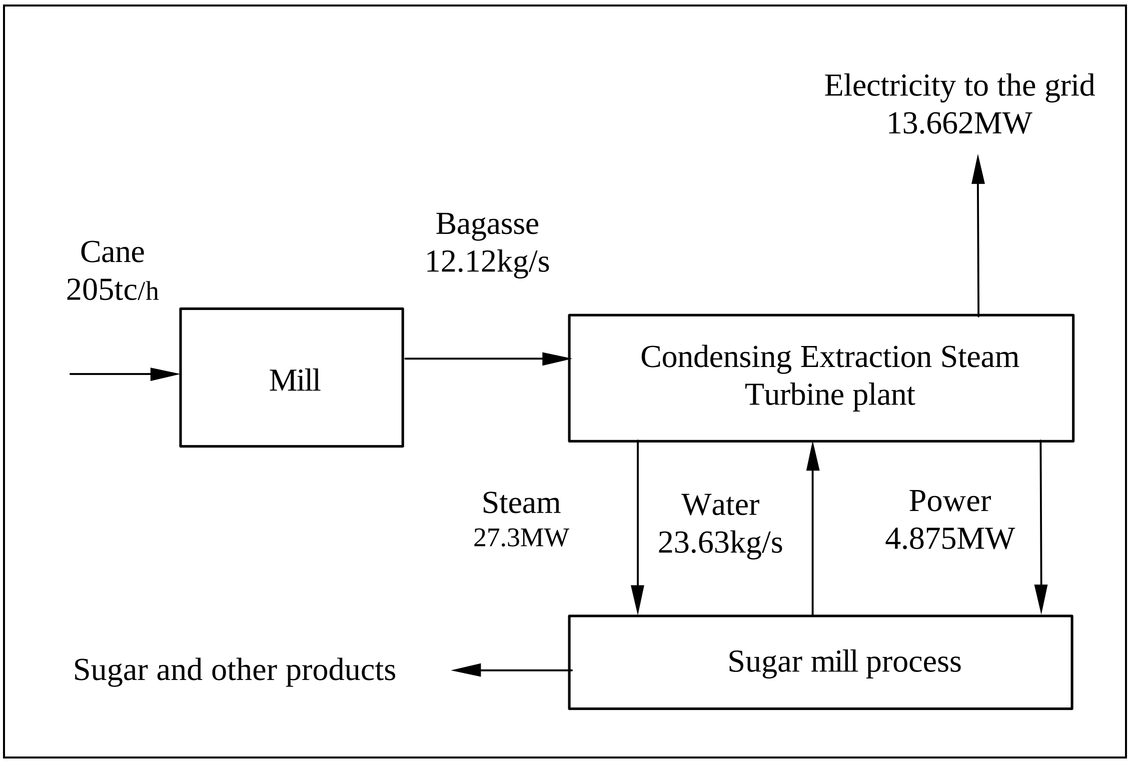

Figure 1- Simplified diagram of CEST technology integrated to sugar mill process. Main mass and energy flows.

2.2 Thermodynamic calculations results (BIG GT technology)

The results of thermodynamic calculations for the BIG GT technology integrated to sugar mill process are shown in Figure 2.

2.3 Thermodynamic analysis.

The thermodynamic calculations results, for both technologies, are given in Table 4. The gas turbine power output is lower than the one specified by the designer, as can be seen in Table 3. Low efficiency is caused by off design operation with the syngas composition given in the Table 3 and high ambient temperature (25 °C). In fact, thermal efficiency is 7 percent lower than that in the design point.

Thermal efficiency regarding only the electric energy produced is relatively low for both technologies . Therefore, thermal efficiency considering all the energy produced (CHP mode operation) is similar to literature referenced values. In all cases, best results corresponds to BIG GT technology.

Thermal conversion efficiencies have been calculated, considering only bagasse as fuel (29% of bagasse per ton of cane). The trash energy potential was not considered, so the system operates only during the crushing season.

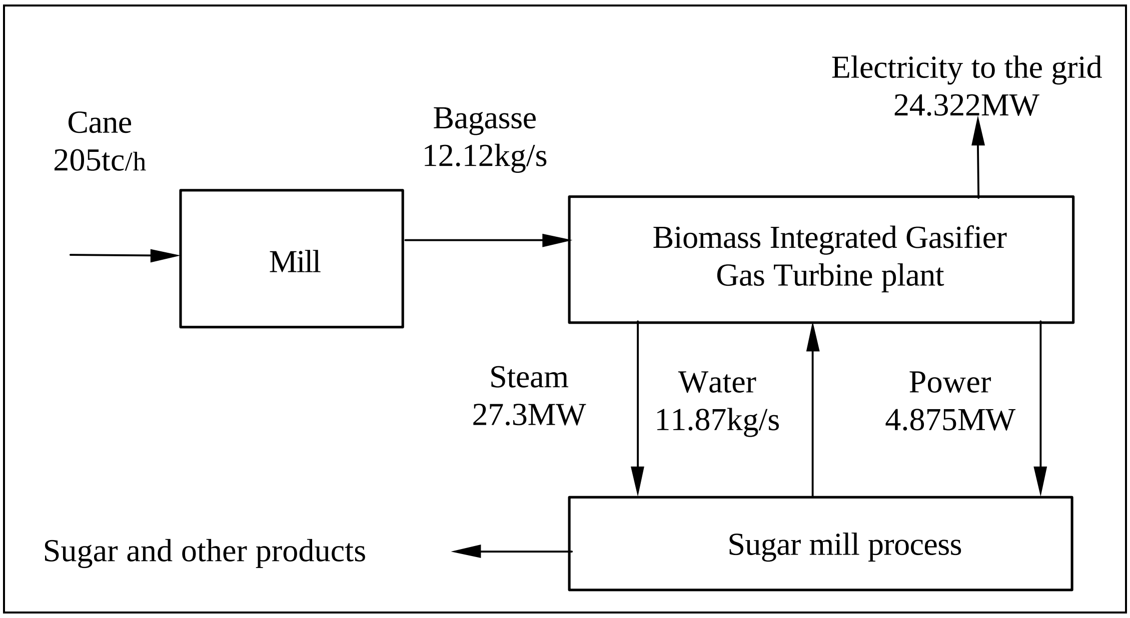

Figura 2- Simplified diagram of BIG GT technology integrated to sugar mill process showing main mass an energy flows.

Table 4. Summary of thermodynamic calculations results

Indicator	Unit	BIG GT	CEST
Gas turbine power output	MW	26.293	-
Steam turbine power output	MW	6.290	18.537
Total power output	MW	32.583	18.537
Auxiliary power consumption [a]	MW	3.386	-
Total electric power available	MW	29.197	18.357
Sugar mill process power consumption	MW	4.875	4.875
Heat to sugar mill process	MW	27.300	27.300
Total energy (I law)	MW	56.497	45.657
h ($HHV_{bag., 50\%W}$)[b]	%	25.00	15.88
h ($LHV_{bag., 50\%W}$)[b]	%	34.30	15.88
h ($HHV_{bag., 50\%W}$)[c]	%	48.41	39.12
h ($LHV_{bag., 50\%W}$)[c]	%	66.38	53.64
Electricity available per ton of cane	kWh/tc	217	124
Heat produced per ton of cane	kWh/tc	182	182
Total energy produced per ton of cane	kWh/tc	399	306
Electrical energy to the grid per ton of cane	kWh/tc	162	91

a) For CEST technology auxiliary power consumption was considered for net boiler efficiency (Table 2).
b) Considering the electrical energy produced.
c) Considering the total energy produced (I Law).

3 ECONOMIC CALCULATIONS

In the economic calculations, was not considered the necessary investment to reduce the process steam consumption in sugar cane mill. In all cases, this investment is assumed to be included in the cost of sugar, alcohol, or other sugarcane mill products. Table 5 shows the main economic calculation assumptions for the both considerations.

3.1 Economic calculations results

The results of the economic assessment calculations had been obtained for two considerations. In Table 6 are listed the principal indicators for both base cases. In case I no steam and electricity are being sold to the sugar cane mill, and no bagasse sold to the BIG GT or CEST plant. In case II, steam and electricity are being sold to the sugar cane mill, and bagasse sold from sugar cane mill to the BIG GT or CEST plant.

Table 5 Main assumptions for economic calculations

Indicator	Unit	CEST	BIG GT
1997 US$	-	Yes	Yes
Project life	Year	30	30
Construction period [a]	Year	One	Two
Operating time	hours per year	4000	4000
Load capacity factor	%	95	95
Federal and state income tax rate	%	30	30
Depreciation		Lineal	Lineal
Investment cost	US$/kW	1200	1700
Variable O & M	US$/MWh	5	8
Fixed O & M	MUS$/year	0.35	0.445[b]
Cost security factor	% of total inversion per year	0.3	0.5

a) After construction the first operation year will be at 75% of full load capacity for both technologies.
b) Source (Craig & Mann, 1996) for 4000 hours of operation per year.

Table 6. Indicators for each economic calculation

Indicator	Unit	Case I		Case II	
Technology	-	BIG GT	CEST	BIG GT	CEST
Electricity for sale	MW	24.322	13.667	29.197	18.357
Steam for sale	MW	0	0	27.3	27.3
Electricity price	1997 US$/$MW_e$h	50	50	50	50
Steam price[a]	1997 US$/$MW_t$h	0	0	15	15
Fuel price	1997 US$/$t_{bag.}$	0	0	10	10
Investment cost	1997 US$/kW	1700	1200	1700	1200

a) Estimated by exergetic cost theory.

In figure 3, for case I, the variation of the present liquid value (PLV) versus project life is shown. The investment recovery period for CEST technology is half of the one obtained for BIG GT technology.

The relationship between electricity price and the internal rate of return (IRR) is shown in Figure 4. Best economic results are obtained for CEST technologies.

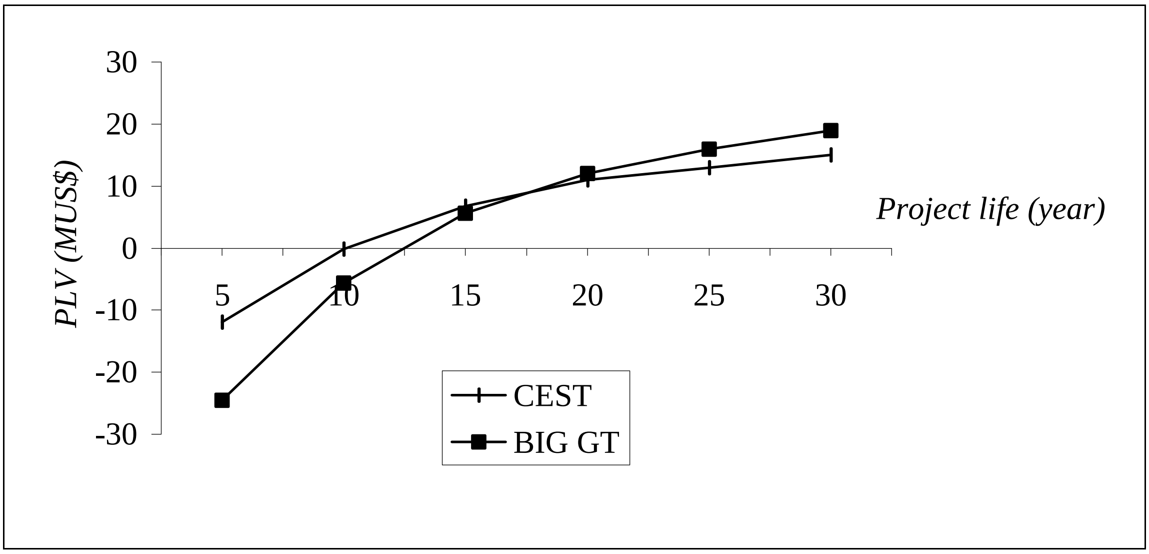

Figure 3- Variation of Present Liquid Value (PLV) versus Project life for Case I with 50 US$/MWh and 8% of IRR.

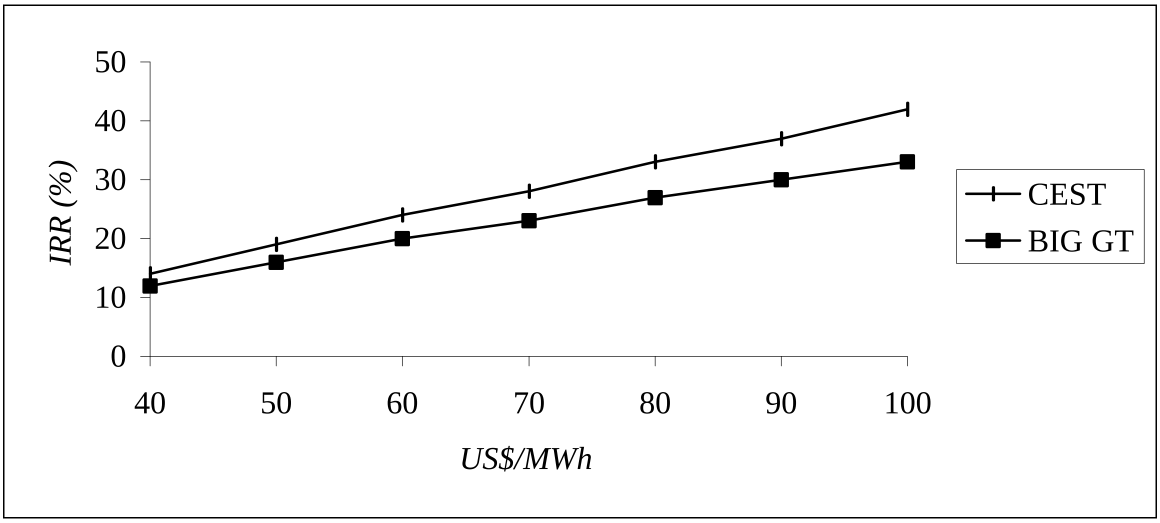

Figure 4- Relationship between electricity price and Internal Rate of Return (IRR) for Case I.

In figure 5, for case II, is shown the variation of the present liquid value (PLV) versus project life. The investment recovery period for CEST technology is lower compared with the one obtained from BIG GT technology. In this case, the investment recovery period is reduced in four years for both technologies, CEST and BIG GT.

The relationship between electricity price and internal rate of return is shown in Figure 6. The best economic results are obtained for CEST technologies having lower low electricity cost for the whole fuel price range.

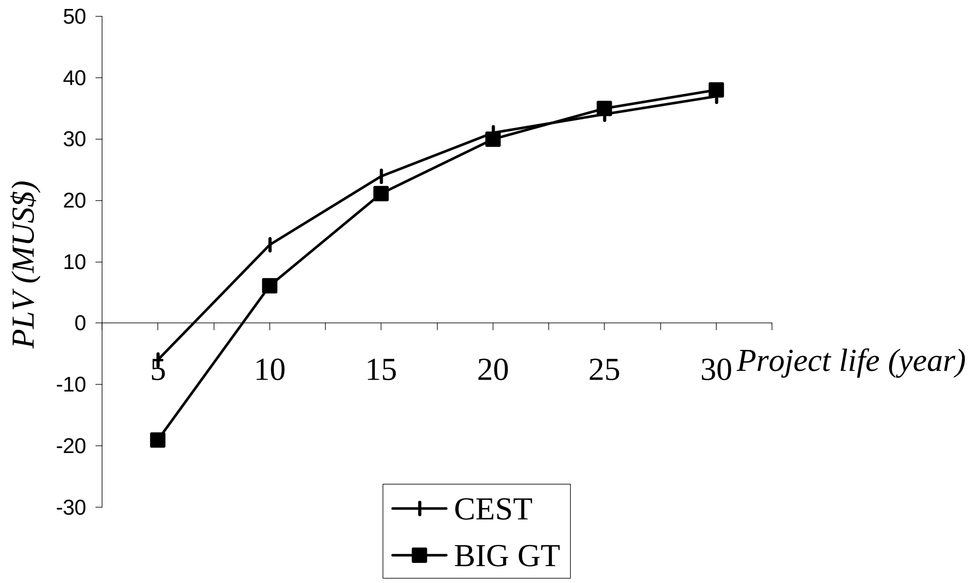

Figure 5- Variation of Present Liquid Value (PLV) versus Project life for Case II with 50 US$/MWh and 8% of IRR.

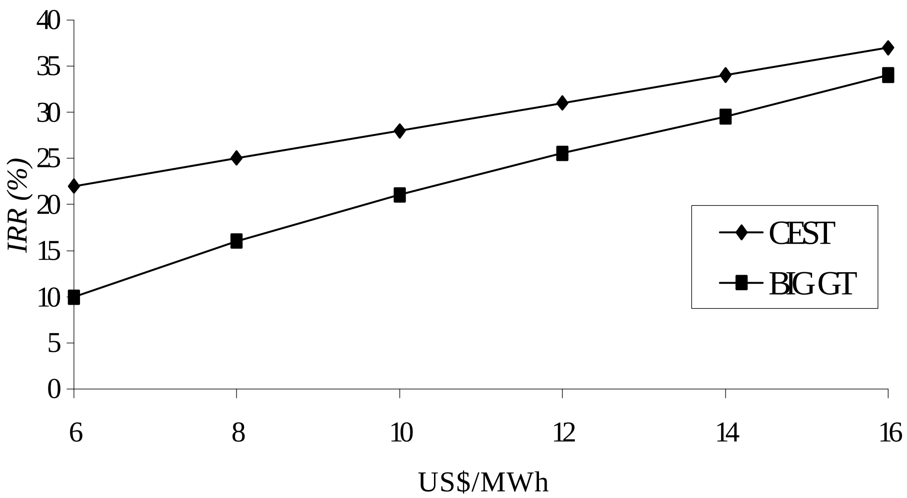

Figure 6- Relationship between electricity price and IRR for Case II.

4 CONCLUSIONS

From the thermodynamic and economic assessment of an integrated power plant using the Condensing Extraction Steam Turbine (CEST) and the Biomass Integrated Gasifier Gas Turbine (BIG GT) technologies for a 205 tons of cane per hours milling capacity sugar mill, is possible to draw the following conclusions:

- The best thermodynamics operation results could be achieved for BIG GT technology. Almost twice more electricity can be sell to the national grid. The power reduction in the gas turbine, while operating with low calorific value gas affects the economic indicators of BIG/GT systems.

- Under the present BIG/GT systems technological development and economic conditions, best financial results could be achieved for CEST technology, when it is applied in a 205 tc/h sugar cane mill. Electricity cost and pay-back period are lower for this technology.

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