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Case Study

Thermodynamics, thermoeconomic and economic analysis of sugarcane biomass use for electricity production: A case study

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This work allows the thermodynamics, thermoeconomic and economic analysis of the cogeneration system of an industrial plant. Two settings were studied: the current that produces electricity only for its own, and secondary, a plant working at high pressure and high temperature using extraction steam turbines to drive an electricity generator and produce 32 MW and a backpressure turbine capable of producing 12 MW. In this case, a high investment is necessary and therefore, a considerable amount of energy sales. The thermodynamic analyses allow the evaluation of some performance indices. The thermoeconomic analysis proposes the distribution of costs based on thermodynamic concepts, enabling the evaluation of reflection of the investment costs and fuel in the cost of products (steam and electricity). The economic analysis acts as a deciding factor for acceptance or project rejection.

Key words: Cogeneration, economic, thermodynamics, thermoeconomic.

INTRODUCTION

With regards to electricity generation, it was observed as a more centralized world electric system during the last century mainly, due to the structure and transmission of power over long distances. However, factors such as the rise in the cost of electricity related environmental policies the recession of production in industrialized countries and the oil crisis, accelerated the reformulation process in industry and sparked the need for change. The quest for improvement in the Brazilian energy system became more evident in 2001 due to the blackout. To Baer (2003), this blackout was due to the drought that occurred three years before it decreased the level of reservoirs and the lack of government planning. According to the author, electricity consumption increased by 5% from 1980 to 2000, while the capacity increased by 4%. As a result of this crisis, the research around the

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CHP became the fastest growing and generating a process of priority and decentralization character, which has encouraged the search for other sources of energy. To Rezac and Matghalchi (2004), the introduction of a "clean" cheap available energy has the ability to promote governments, improve the economy of poor countries, provide basic sanitation and increase the health benefits, as well as reducing the amount of pollutants entering our atmosphere in the form of greenhouse gases coming from human activities.

According to Dantas (2010), cogeneration is a process in which a primary energy source feeds an apparatus or heat engine and through a combustion reaction it accomplishes the conversion of chemical energy of the fuel into mechanical shaft. The same is converted into electricity in the electric generators. Therefore, the thermal energy from the hot combustion gases can be used directly or converted into another form of useful energy such as steam. This scenario created by the need for development and use of new energy sources is largely favorable to the use of biomass for electricity generation. When derived from sugarcane, biomass is made up of high levels of lignocellulosic materials, which are great producers of thermal and electrical energy (Oliveira et al., 2009). However, despite the discussion of cogeneration for sale of electricity in Brazil has begun many years ago. The results achieved so far are not very significant. Among the many reasons that contribute to the current framework included, the institutional barriers still existing in the country, the culture and conservatism prevailing in the electricity sector, the importance and extent of hydropower potential, lack political definitions with a view enabling other options for expansion and due to low investment in this type of energy.

According to Mizutani (2013), if all the plants of this sector in Brazil produced electricity from biomass, there would be 1.5 times more energy than the Itaipu hydroelectric plant is capable of generating. The use of waste from sugarcane represents, therefore, a possible viability of expanding the capacity of electricity generation from a technology already available with low investment in research (Walter, 1994). Within this context, the use of biomass from sugarcane for energy purposes contributes to the energy supply in periods of drought and energy crisis, besides acting as a source of energy that does not harm the environment.

In this bias, the development of this research allows the modeling and simulation of thermodynamic, thermoeconomic and economic analysis of the cogeneration system of industrial plant in a sugarcane mill. Two settings are analyzed; the current that produces electricity only for own consumption (with its plant already amortized) and a plant working at high pressure and high temperature with extraction-steam turbine capable of driving an electricity generator to producing 32 MW and a backpressure turbine capable of producing 12 MW. Thus, we analyzed the feasibility of implementing a thermoelectric plant.

MATERIALS AND METHODS

Elements of energy analysis

The solution to the problem addressed in this article involves the basic principles: The first and second law of thermodynamics. Whereas, the control volumes are steady, neglecting the kinetic and potential energies we can write the first law as follows (Borgnakke et al., 2009):

$$\dot{Q}_{v.c.} - \dot{W}_{v.c.} + \sum \dot{m}_e . h_e - \sum \dot{m}_s . h_s = 0 \quad (1)$$

Where, $\dot{Q}_{v.c.}$ is rate of heat transfer in the control volume (kW); $\dot{W}_{v.c.}$ is rate power for the control volume (kW); $\dot{m}_e$ and $\dot{m}_s$ is mass flows entering and leaving the control volume, respectively (kg/s); h_e and h_s is specific enthalpy at the inlet and outlet of the control volume, respectively (kJ/kg).

The first law of thermodynamics defined the property of internal energy which led to the definition of enthalpy and allowed to analyze the processes within a system in a quantitative way. The second law of thermodynamics defines the property of entropy which allows the realization of a quantitative and qualitative analysis of the processes. This refers to the quality of energy and direction of energy flow taking as postulate the claim that the heat will flow from the highest to the lowest temperature with no heat flow if these variables are of equal value. In this principle it is also verified that there is no reversible natural process, that is, each process involves the degradation of energy resources then being irreversible (Borgnakke et al., 2009).

Almeida (2005), states that the analysis of the first law does not account for the quality of the energy lost or where the irreversibility occur. The combination of the first and the second law may establish the energy balance and calculate the irreversibility in the processes. For processes in continuous operation the irreversibility generated can be given by:

$$\dot{I}_{v.c.} = \sum \dot{Q}_{v.c.} . \left(1 - \frac{T_0}{T_{v.c.}}\right) - \sum \dot{W}_{v.c.} + \sum \dot{m}_e . ex_e - \sum \dot{m}_s . ex_s \quad (2)$$

Where, $\dot{I}_{v.c.}$ is irreversibility rate in the control volume (kW); T_0 is reference temperature (K); $T_{v.c.}$ is surface temperature of the control volume (K); ex_e and ex_s is specific entropy at the inlet and outlet of the control volume, respectively (kJ/kg.K).

Elements of exergy analysis

Rant (1956) was the one who proposed the word exergy to replace various terms of similar meanings employed in different countries, useful energy (France), availability (USA) and work capacity (Germany). This author also proposed the word anergy which is the part of the non-utilized energy or better: Energy = Exergy + Anergy. Energy therefore, is all that can be tapped (exergy) added to that which is not useful (anergy). In other words, energy is that which can be converted into heat and/or work. However, to calculate the exergy is necessary to define the reference state in order to have a basis on which values are to be adopted. For Szargut et al. (1988) exergy is the amount of work obtained when a mass is brought to a state of thermodynamic equilibrium with the common components of the environment. According to the author, the total exergy a given flow or fluid can be subdivided into potential, kinetic, chemical and physical exergy. In a cogeneration system disregarded the kinetic and potential exergies, so the flow energy of a fluid is given only by the sum of physical and chemical exergies.

$$ex_{tot} = \frac{(h-h_0)-T_0(s-s_0)}{I} + \frac{\sum(\mu_i-\mu_{0,i})x_i}{II} \quad (3)$$

Where, T_0 is reference temperature; $\mu_{0.i}$ is refers to the element's reference chemical potential($T_0 . P_0$); μ_i is element's chemical potential in the mixture($T_0 . P_0$); x_i is the component fraction in the mixture. The dead state or reference environment is indicated by the subscript "0". The reversible work will be maximum when $s_s = s_0$ e $h_s = h_0$.

Making use of the idea of an environment that represents the real physical world, the standard conditions of temperature and pressure will be used as reference environment (STP). T_0=298.15K and P_0=101.325 kPa.

Performance indices of cogeneration systems

Ensinas (2008) mentions that generation plants of conventional power and cogeneration systems have different conceptions. Plants of power generation (usually electricity) seek to have maximum efficiency, while cogeneration projects is require to meet the demands of heat and power. Since both products have their advantages and needs according to the production, the calculation of electrical efficiency has become a performance criterion suitable for use. The goal of using performance indices to evaluate the cogeneration systems as a whole, clarifying the differences among them, particularly with respect to the application of methods based on the first and second laws of thermodynamics. The cost effectiveness of a cogeneration system is directly related to the amount of electricity that a system is able to produce for a given amount of heat used in the process (Barreda del Campo, 1999).

$$\mathrm{RPC} = \frac{\dot{W}}{\dot{Q}_U} \qquad 4$$

Another important parameter is the ratio electric power generated and the amount of crushed cane.

$$R_{pot\_elet/cana\_moi} = \frac{\dot{W}_{elet}}{3.6 . \dot{m}_{cana\_moi}} \qquad 5$$

Where, $\dot{m}_{cana\_moi}$ is amount of cane crushed (kg/s); $\dot{Q}_U$ is useful heat (kW).

Other measures could be used such as the energy use factor, the overall efficiency, the rate of energy saving, energy to be saved and rate of power generation. However, as the same amount of bagasse is not consumed in both case, it is not possible to compare them effectively.

Thermoeconomic elements

The thermoeconomics is a methodology developed based on the concepts of exergy for analysis of thermal systems. For the dissemination of thermoeconomic analysis, is necessary to perform an Exergy analysis followed by an economic analysis. This methodology has a main objective to assign costs to an energy carrier (Jaramillo, 2011). This article uses the exergoeconomic methodology that makes use of the allocation of average costs of equipment being able to determine the cost of products to provide a means of allocating costs and act as a base for making operating decisions. This methodology elaborated by Reistad and Gaggioli (1980) for the exergoeconomic methodology, when formulated for a balance of cost individually in each k-component system. It follows that the sum of rates of all input exergetic flows over the price due to the capital investment and operating costs and maintaining each k-component is equal to the sum of cost rates associated with all the exergetic flows out of the system.

$$\sum_e c_e(\dot{m}_e . ex_e)_k + (c_Q . \dot{Q})_k + \dot{Z}_k = \sum_s c_s(\dot{m}_s . ex_s)_k + (c_W . \dot{W})_k \qquad 6$$

Where, c is average flow cost per time unit in the component k (R$/s);

Economic elements

The use of economic analysis as investment decision aims primarily at assisting and evaluating one or more alternatives to determine the more attractive means of action from quantitative methods. This type of analysis when used as a form of aid in the purchase or expansion of an enterprise should present decisive results for acceptance or rejection of the proposal analyzed. According to Gitman (1984) the best techniques for capital investment make use of the time factor in the future value of money and consider the cash flow over the project life. The VAL method explicitly demonstrates the actual net profit that the investor should receive over the project life. It is obtained by subtracting the initial investment in a project from the present value of the cash flows discounted at a rate equal to the cost of company capital, that is, it determines the total net value of the investment discounted to the Minimum Rate of Attractiveness (TMA) on zero date. The MRA is an interest rate that represents the minimum that an investor intends to gain when there is investment.

$$\mathrm{VAL} = \frac{\mathrm{BEN}}{(1+j^*)^N} - \mathrm{CTI} \qquad 7$$

The equation to describe the VAL is used as criterion of "acceptance" or "rejection" of a given project. If the VAL value is greater than zero, the project can be accepted because the cash inflow is greater than the cash outflow. In the case of VAL be equal to zero, the investment is irrelevant since the inflow is equal to the outflow. Otherwise it must be rejected.

Method of solution

The equations can be solved by using any suitable calculation tool for this purpose. However, the ESS® software (Engineering Equation Solver) developed by Klein and Alvarado (1995) was used, which allows determination of thermodynamic properties such as the enthalpy and entropy in a simple and efficient way without the need to use thermodynamic tables.

CASE STUDY

Case 1: Current

The data cited in Table 1 refer to the production of sugarcane in the 2012/2013 harvest a plant of sugarcane industry located within the Paraná. The company works on two boilers of 21 kgf/cm^2 and only with backpressure turbines. The generator turbo is used only for internal power consumption of the establishment (administrative, kitchen, rooms in general) and not for driving the mills, hoods, fans and pumps as shown in Figure 1.

Case 2: Suggested

In case 2, studied the hypothetical configuration which has one or more modern steam plant with more efficient equipment, all electrified, aimed at expanding the case 1. The boiler proposed produces 200 t/h steam at 66 kg/cm^2 and 530°C. 140 t/hr of this steam is consumed by the extraction steam turbine coupled to a generator of 32 MW. An extraction of 100 t/h of steam is performed

Table 1. Data on grinding, consumption and production of bagasse in the 2012/2013 harvest.

Parameter	Value	Unit
Total cane crushed	1.970.165	t
Harvest period	282	Days
Days effective crop	231	Days
Daily Grind	8.520	t/day
Grinding time	355	t/h
Fiber content of the cane	12.5	%
Fiber content of bagasse	47.4	%
Flow of bagasse in the boiler 1	34.6	t/h
Flow of bagasse in the boiler 2	37.3	t/h
Flow bagasse in boilers	71.9	t/h
Stream full bagasse produced	92.45	t/h
Flow residual bagasse	20.55	t/h

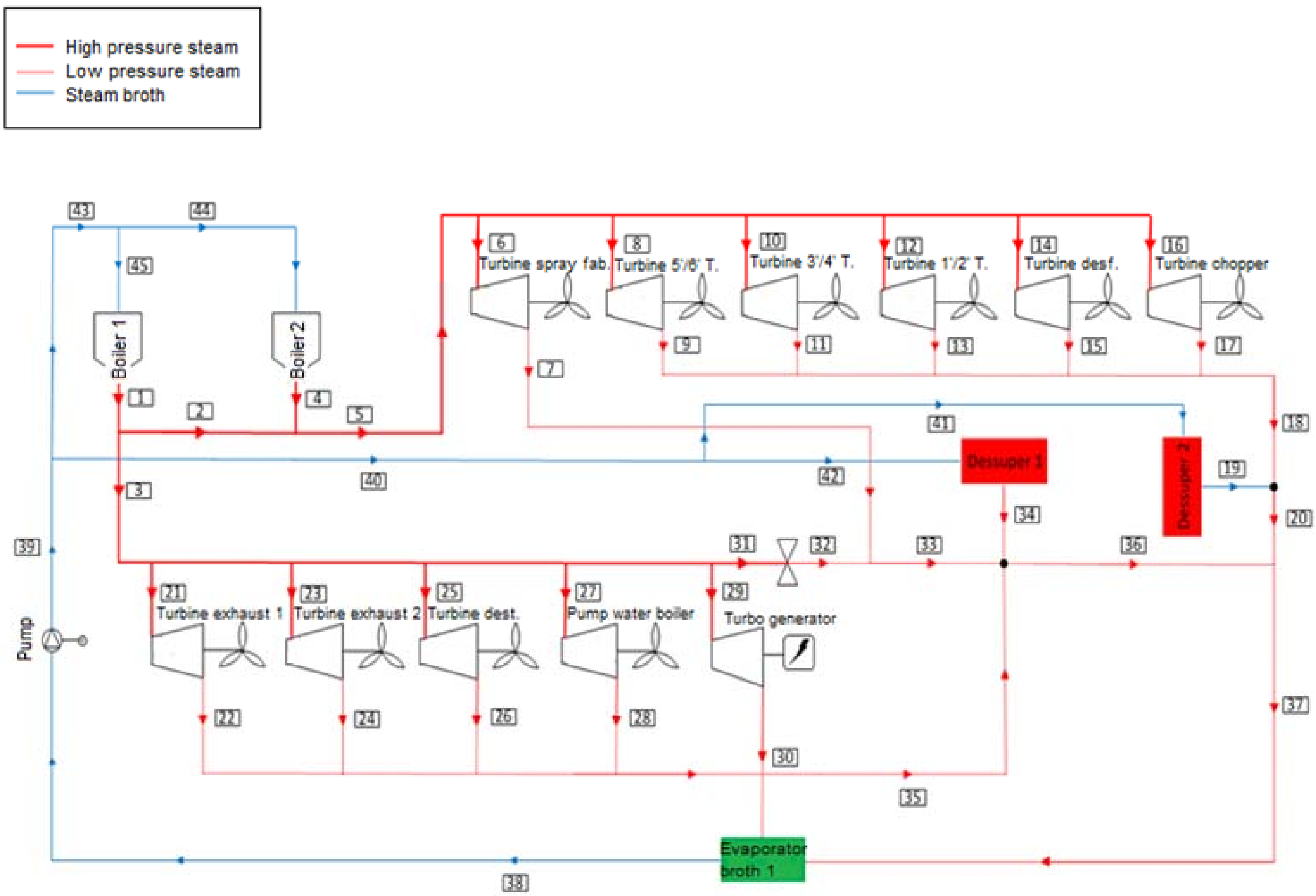

Figure 1. Current plant under analysis.

at a pressure of 245 kPa for the evaporation process of the broth and the remaining steam continues to expand until the pressure of 8 kPa and then condensed. The rest of the steam produced 60 t/h is consumed by a backpressure turbine and capable of generating 12 MW. In this case, the steam is discharged at a pressure of 245 kPa also designed to meet the steam demand in the industrial process as shown in Figure 2. The boiler 2 can be used in exceptional cases as it is already amortized (same boiler of Case 1). However, only the boiler 1 will be use for simulation. According to suppliers, this new boiler would have efficiency of 2.165 kgV/kgB.

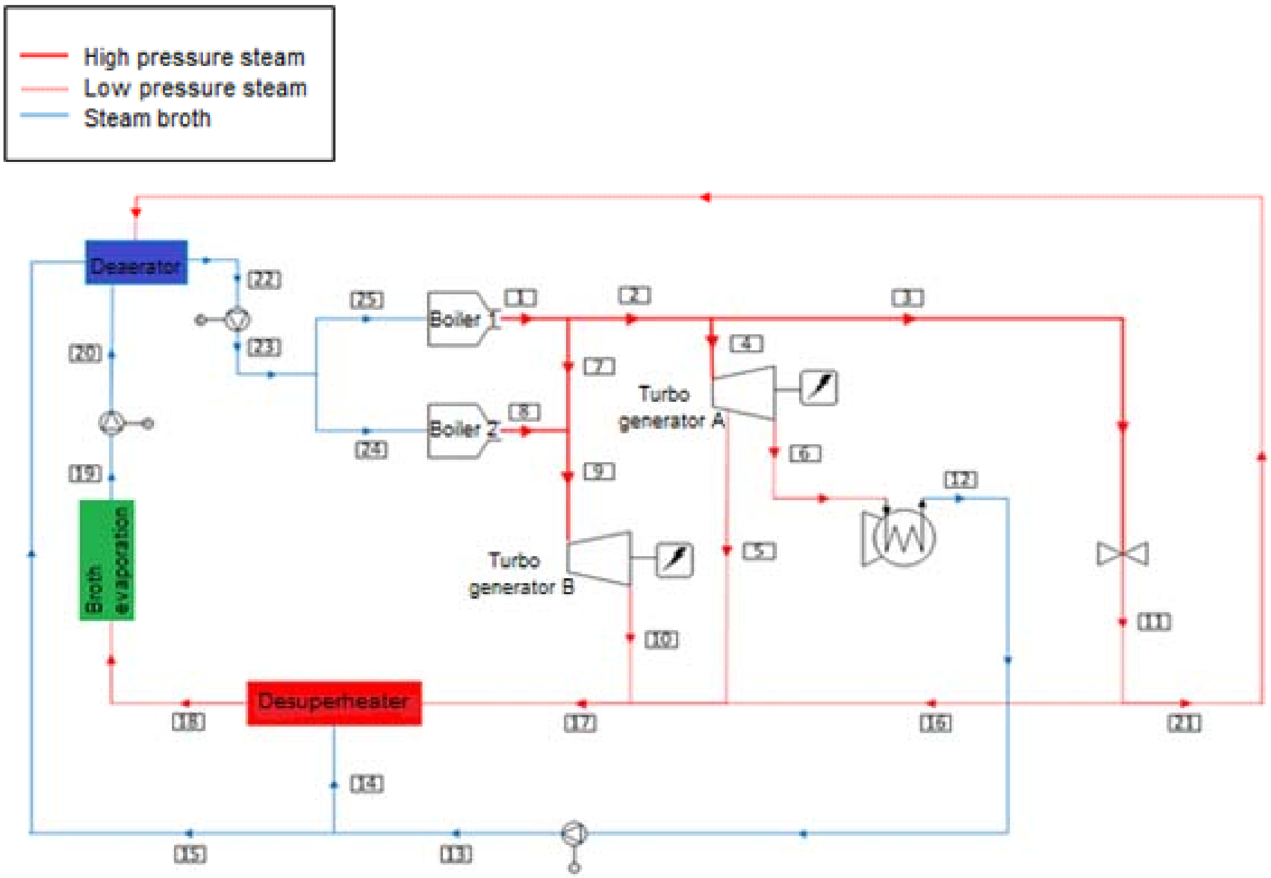

Figure 2. Plant suggested.

Table 2. Bagasse consumption of the crop.

Parameter	Value	Unit
Flow of bagasse in the boiler 1	92.45	t/h
Flow of bagasse in the boiler 2	0	t/h
Flow bagasse in boilers	92.45	t/h
Flow full bagasse produced	92.45	t/h
Flow residual bagasse	0	t/h

The milling data are considered as the same in Table 1 with the difference that the boiler 1 consumes the entire bagasse production according to Table 2. Table 3 shows the power generated or consumed by each device in each case analyzed.

RESULTS AND DISCUSSION

For simulations it was used as a value of 7736 kJ/kg for the LCV (Lower Calorific Value) of bagasse and for the value of its exergy was adopted 10.170 kJ/kg.

Thermodynamic results

The current plan – Case 1 needs 10859.7 kW to meet its demand. Undoubtedly, this demand would be lower due to the higher efficiency of its generators. Table 4 shows the performance indices for two cases.

Thermoeconomic results

The annual cost of equipment with amortization was calculated taking into account a depreciation period of 20 years. The interest rate of 12% was considered. The value of R$ 15/t was taken as reference which is the price adopted for the bagasse sale between the plants at harvest season. Figure 3 shows the cost of electricity produced depending on the bagasse cost. It is found that the cost of electricity generated is R$ 88.02/MWh and R$107.5/MWh for the current and suggested case respectively. Macedo et al., (2004) estimate that the rate of production of bagasse can reach 280 kg per tonne of cane crushed with 50% moisture content and lower calorific value of about 7500 kJ/kg. Figure 4 represents the cost of electricity produced and the cost of process steam depending on the bagasse cost for the current and suggested case. It is observed in this case that the cost of process steam is R$ 20.73/t and R$ 10.76/t for the current and suggested case respectively.

Table 3. The power generated or consumed by each device in each case analyzed.

Parameters/case 1	Case 1 (kW)	Parameters/case 2	Case 1 (kW)
Cop Chopper 8	1.500		
Shredder	1.500		
1 ° and 2 ° Suits Milling	1.120		
3 ° and 4 ° Suits Milling	1.120		
5 ° and 6 ° Suits Milling	1.120	Turbo Generator A	31.807
Turbo Pump Water Boiler	326.7	Turbo Generator B	11.850
Turbo Pump Distiller	200	**TOTAL**	**43.657**
Turbo Spray	676		
Exhaust 01	161		
Exhaust 02	184		
Turbo Generator	2.952		
TOTAL	**10.859.7**		

Table 4. Performance rates.

Cases / parameters	RPC	$R_{pot\_elet/cana\_moi}$
Current	0.0888	39.88
Suggested	0.3421	124.7

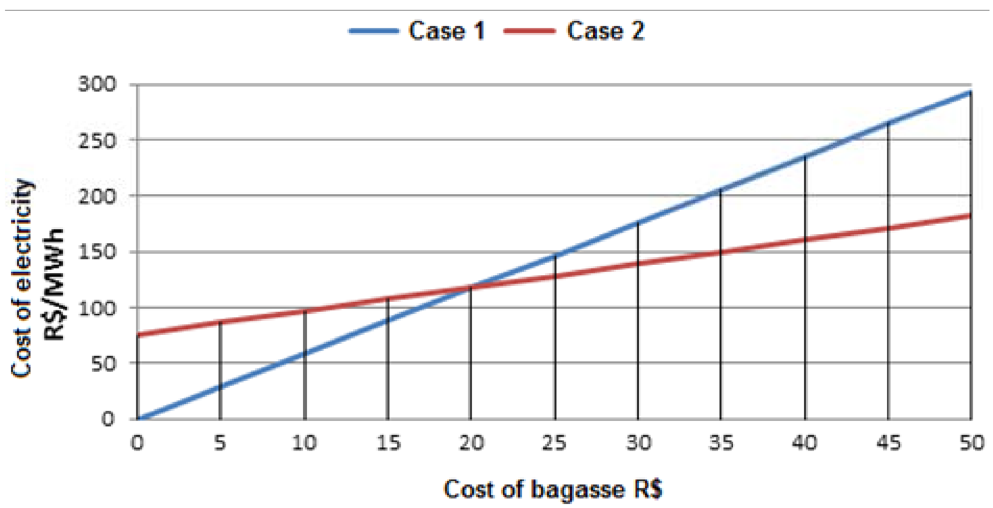

Figure 3. Electricity cost x bagasse cost.

Economic results

The plant of Case 1 is already amortized, therefore, it will only performed the economic analysis of case 2. The internal power consumption will be considered the same 10859.7 kW, thus the excess electricity is 32796.3 kW. The bagasse cost will be considered R$15/t and the total cost of deployment will be R$ 78.4 million, accounting that 40% of the investment refers to the installation, labor, maintenance among others. Table 5 shows the economic indicators related to industrial plant suggested. The plant begins to have return of investment setting the selling price of electricity in R$ 165.22/MWh for a rate of investment return of 12%. Figure 5 shows how cash flow would behave for the case supposed from the sale of electricity at a price of 160, 170, R$ 180/MWh.

This work corroborates with Dantas (2009), in their work with energy generation from bagasse, concluded increased attractiveness for investments in this segment providing positive results to investors. Pellegrini and

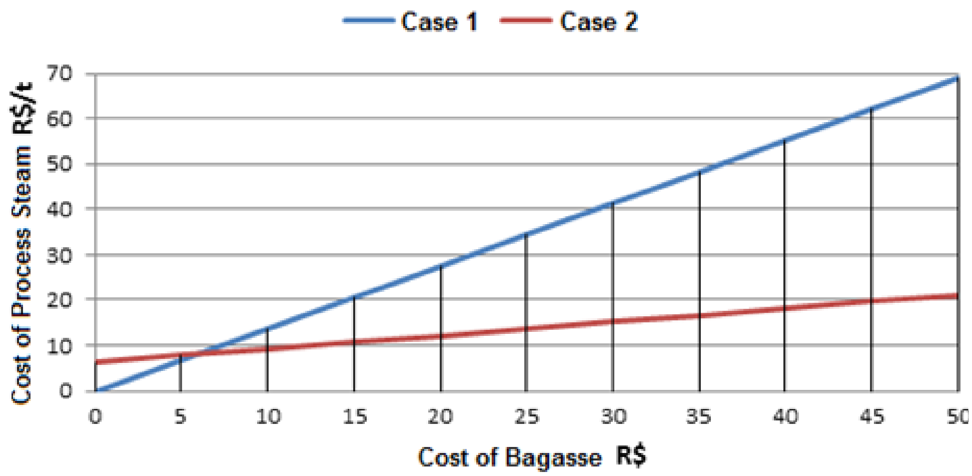

Figure 4. Cost of steam process x bagasse cost.

Table 5. Economic indices concerning the second plant.

Sale price	NPV (R$)	ITR (Years)	IRR
R$ 160/MWh	-R$ 7.096.824.58	0	10.5328%
R$ 170/MWh	R$ 6.484.732.64	15.53919388	13.3029%
R$ 180/MWh	R$ 20.066.289.86	11.03723914	15.9417%

Net present value (NPV), Internal Time of return (ITR), Internal Rate of Return (IRR).

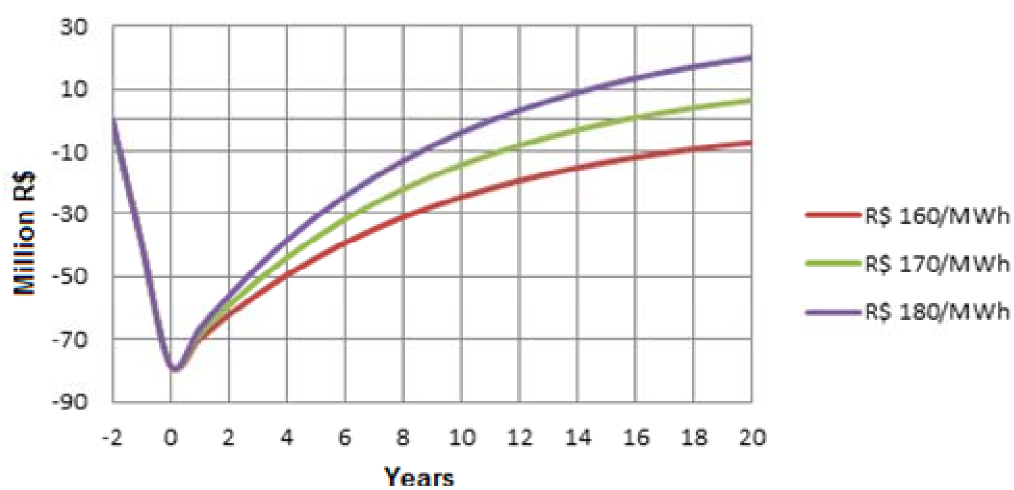

Figure 5. Cash flow for the supposed case.

Oliveira (2011) show the study about production of sugar, ethanol and electricity, that the generation of excess electricity improves the exergo-environmental performance of the mill as a whole. Nadaletti et al. (2014) comments that the use of another energetic plants, like canola (Brassica napus L. var. oleifera Moench.) in large production in Brazil, can be a alternative to agroenergetic purposes.

Conclusions

The thermodynamic analysis of plants demonstrated that the uses of an extraction-steam turbine can double the amount of energy produced by the plant. There is also highest amount of electricity produced compared to thermal energy through the performance indices. Considering the amount of R$ 15/t it is observed in the thermoeconomic and economic analyses that the deployment of a modern and efficient plant will not significantly increase the cost of process steam and investment becomes attractive only when the selling price of energy reaches R$ 165.22 MWh being unfeasible to lower values. An alternative would be to reduce the cost of bagasse for the same amount of electricity produced, thus the project would be accepted with a lower selling price of energy. The difficulties inhibiting the development of this segment are not related to the feasibility of developing or deploying a new industrial plant. Since, we consider that it is largely feasible, the expansion and production of electricity at a sale price are less than other energy sources and yes the lack of a clear policy of inclusion of this segment is in the national energy and power matrix.

Conflict of Interests

The author(s) have not declared any conflict of interests.

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