TECHNICAL AND FINANCIAL OPTIMIZATION OF A COGENERATION PLANT IN A SUGAR AND ALCOHOL PLANT WORKING WITH VARIABLES LOADS

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Abstract. *In the design of a thermal plant both financial and technical aspects must be taken into account simultaneously. The assesment of the exact costs and real technical characteristics of the equipments rises the time and cost of the design. Another important design practice is to consider the behavior of a plant when operating off-design. There is no alternative to a good design but performing both studies. The main aim of this paper is to perform a series of studies over a generic plant in order to determine the ability of technical indexes (as energetic and exergetic efficiencies) to specify the most financially viable plant. Other study is the analysis of the financial robustness of the plant, i.e, its ability to remain financially viable despite variations on the loads. Finally the financial robustness of the plant is tested against the variation on the selling values of the products (alcohol, sugar and electricity). The object of study is a cogeneration plant with average power of 70MW, composed of a boiler, a backpressure turbine with 50MW that provides steam for the sugar/alcohol production and a condensation turbine of 20MW. The paper reaches several important conclusions for this specific case: a) the initial plant configuration continues to be the better one despite variation on the loads and on the product selling values, b) both the energetic and exergetic efficiencies points to the most financially viable plant and c) the plant is very flexible in respect to variation on the load,s remaining financially viable despite 15% variation on the loads.*

***Keywords**: Cogeneration, financial analysis, energetic analysis*

1. INTRODUCTION

The Brazilian energy market has been continuously expanding on the last decade but this strong growth with a lack of investment in the diversification of energy sources caused a sever energy crisis in the country a few years ago. This occurred because the Brazilian energy matrix is mainly hydroelectric. This is good by one hand because hydroelectricity is a renewable source. But the drawback of any energy source when used practically alone is its fragility to any kind of shortages. In the case of hydroelectricity a prolonged drought can severely diminish the power generation of the country. After this energy crisis Brazil began to diversify its energy matrix. The sugar cane plants have a large potential for electricity generation because the combustion of the bagasse resulted in the milling process is more than enough to product both the steam for the alcohol and sugar process and the mechanical energy necessary for the milling process itself. The remainder bagasse can be used to produce more steam than necessary in the process. The additional steam can be used on a turbine to produce electricity for selling. Lora and Andrade (2007) show several possible cycles in order to use biomass in electricity generation.

The analysis of power plants of sugar and alcohol is of extreme interest for scientific reasons because of its ability for generating clean electrical energy and clean fuel. It is also very important to study those plants on the financial aspects because although the plants can be highly viable they are highly costly too.

There are several works on power plants simulation. Dunn e Flavin (2000) present technologic alternatives for small scale power generation based on each country situation. Khan and Rasul (2004) performed a comparison between cogeneration systems with and without thermal storage. Cardona and Pacentino (2003) presented a methodology for the study of trigeneration systems used in offices. Szko and Tolmasquim (2001) present actions of the Brazilian government for the increase of natural gas use. Míguez et al. (2004) presented a new system of trigeneration to residential use. Additionally they studied various operational methods in order to optimize the system. Ho et al. (2004) performed studies on a cogeneration system in which the loads and the periods of operation of the turbine and the absorption chiller were varied. Vieira et al. (2004) showed an automatic methodology for the exergetic and financial optimization of thermal systems. Carraretto e Lazzaretto (2004) presented a model where the total generation of energy is limited by financial conditions and the studies are performed varying prices of fuels and electricity. Wischhusen and Schmitz (2004) presented the advantages of dynamic simulations over static simulations when analyzing thermal systems. Knight et al. (2004) describe an analysis of a cogeneration plant based on the economics performance. Manolas et al. (1996) present the use of genetic algorithm in the optimization phase. Accadia (2001) presents a comparison between various operation modes in a steady state plant. Gamou et al. (2002) optimize a cogeneration power plant with daily variations with uncertainties in the energy demand. Magnani and Melo (2009) presents a method to generate highly flexible computational models to use on the financial optimization of thermal plants operating on variable loads.

The present work begins with the description of the plant to be studied, followed by the calculation of the technical and financial indexes used on the selection of the better design. The first study performed is the variation on the loads of the plant, i.e., the analyses of the plant when the steam demanded by the process is increased or diminished. Accompanying the fluctuations of the demanded steam is the variation of the total power generated. The second study is performed maintaining the technical aspects of the plant used in the first study but changing the selling values of the products of the cogeneration plant, namely sugar, alcohol and electricity. The variations are made based on an already optimized plant using nominal loads and selling prices.

Based on the results of the two studies three ample analysis are performed: a) whether the original plant remains the optimum one when the loads are varied, b) whether the original plant remains the optimum one when the selling prices are varied and c) whether the technical indexes (energetic and exergetic efficiencies) points to the same optimum design as the financial indexes (NPV and IRR). If the technical indexes would point to the same optimum as the financial indexes then it was possible to perform only the technical analysis on the optimization of a design. It is not expected that this concordance will be always reached so it is always mandatory to perform the financial analysis of a design. But if in most cases the technical indexes agree with the financial ones then it would be possible to use only technical analysis for the initial choice of studied scenarios.

2. Plant Description

The generic 70 MW plant studied in this paper is thought to be located in the southeastern region of Brazil. The cycle shown on figure 1 is composed of a boiler, a 50 MW backpressure turbine and a 20 MW condensing turbine. The steam exiting the backpressure turbine is used in the milling process and in the production of alcohol and sugar. Each year, on average, the consumption of a plant of this size is 1.440.000 tons of bagasse. In the table 01 are presented the main characteristics of the fuel. Part of the steam from the boiler is used for seaming. The boiler rejects 3.5% of its output flow. The average consumption of process steam is 334 ton/h, i.e., 440 kg of steam for each ton of milled sugar cane. 650 tons of sugar cane are milled per hour.

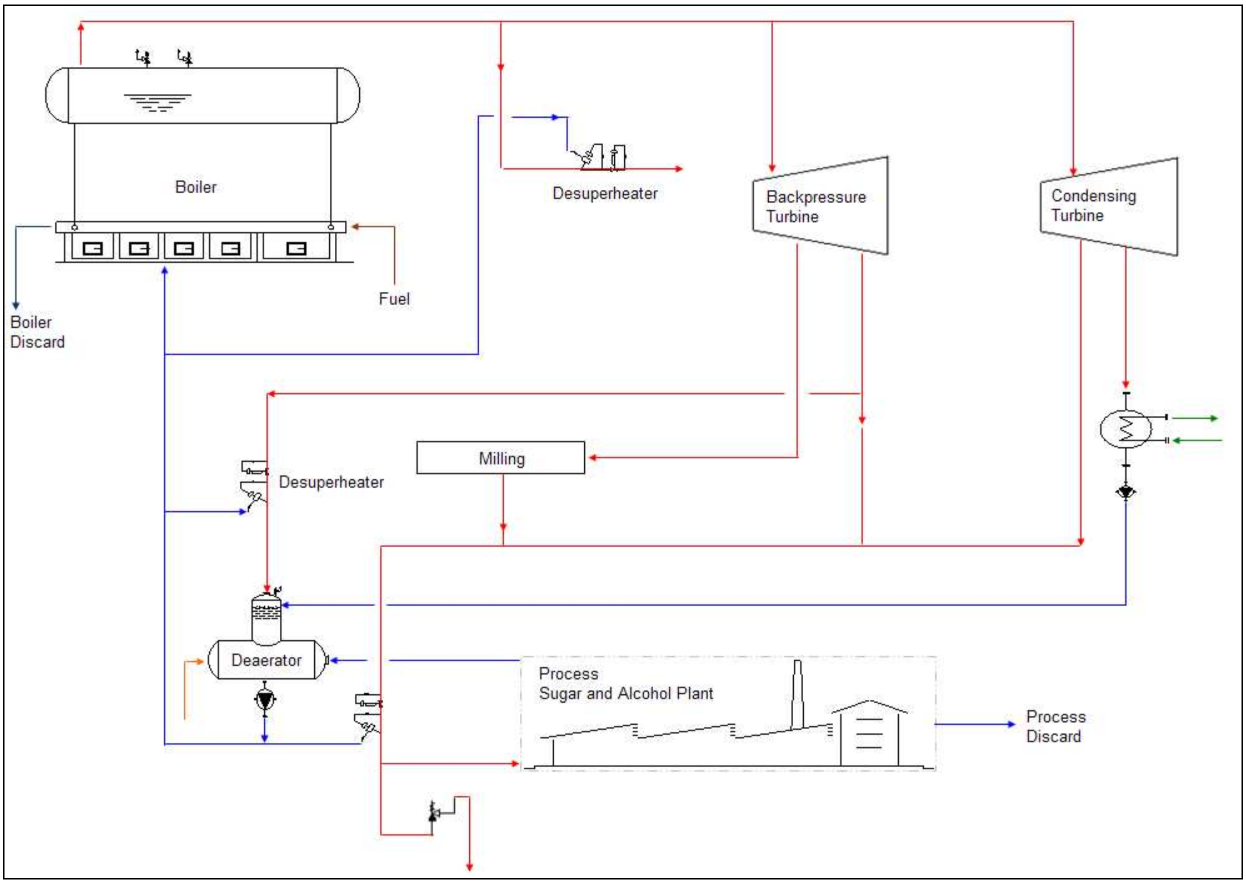

Figure 1. Plant description

Table 1. Fuel – Sugar cane Bagasse

Fuel Composition (% weight)	Carbon (C)	47
	Hydrogen (H_2)	6,5
	Oxygen (O_2)	44
	Ash	2,5
Humidity range (%)		48/54
Fiber (%)		24 [(1)]
LHV average (kJ/kg)		7398,6
HHV average (kJ/kg)		9405,0

(1) On southeastern Region 24% of sugarcane is fiber, in average, value reported by owner of sugar cane Bagasse.

Table 2 presents the values of mass rate, pressure and temperature of the cycle. It can be noticed that the pressure of the boiler is 90 bar, the maximal temperature of the cycle is 520 ºC and the dearator operates at 110 ºC. This plant was previously financially optimized for those given values of pressure/temperature and the loads specified on the first paragraph of this section. In the remaining of this work the loads are going to be varied and the previously optimized plant will be tested based on its ability to support variations on the load and selling values. For this base case the global energetic efficiency (electricity generated plus the energy of steam delivered for the process divided by the energy of the fuel) is 74% and the global exergetic efficiency (electricity generated plus the exergy of the steam delivered for the process divided by the exergy of the fuel) is 63%.

Table 2. Equipments data

Equipment's Point	**Mass flow (t/h)**	**Pressure (bar (a))**	**Temperature (ºC)**	**Fluid State**
Entering the Boiler	400	90	110	Heated Water
Leaving the Boiler	400	67	520	Superheated Steam
Entering the backpressure Turbine	300	63	515	Superheated Steam
Extraction of backpressure turbine	110	21	215	Superheated Steam
Exhaust of backpressure turbine	190	2,5	190	Superheated Steam
Entering the condensing turbine	100	63	515	Superheated Steam
Extraction of condensing turbine	22,5	2,5	190	Superheated Steam
Exhaust of condensing turbine	77,5	0,1	Saturated Temperature (Quality ≈ 92%)	Saturated Steam
Cooling Tower	4000	5	29	Cooling Water

3. Analysis and discussion

For the thermodynamics analysis the enthalpies and exergies of each flux was determined from the data of table 2. Equation 1 shows de definition of the exergy of the mass fluxes. For each equipment it was considered a control volume in which were applied the mass conservation equation (equation 2), energy conservation equation (equation 3) and exergy balance equation (equation 4). With the values of power delivered or consumed by each equipments, the enthalpy and the exergy of the fluxes of mass, it was possible to determine the global energetic efficiency and the global exergetic efficiency of the cycle by equations 5 and 6. The energetic efficiency characterizes how the energy of the fuel is used for the generation of electricity and process steam. The exergetic efficiency quantifies the percentage of the fuel exergy that is delivered by the cycle in the form of electricity and process steam exergy. For the calculation of the exergy of the fuel it was used a simplified model of Kotas (1985).

$$\psi = (h - h_0) - T_0(s - s_0) \tag{1}$$

$$\sum \dot{m}_i = \sum \dot{m}_e \tag{2}$$

$$\dot{Q} - \dot{W} = \sum \dot{m}_e h_e - \sum \dot{m}_i h_i \tag{3}$$

$$\dot{X}_{heat} - \dot{W} = \sum \dot{m}_e \psi_e - \sum \dot{m}_i \psi_i + \dot{I} \tag{4}$$

$$\eta_{I,CYCLE} = \frac{\sum \dot{W}_{NET,OUT} + \sum \dot{H}_{STEAM,OUT}}{\dot{E}_{FUEL}} \tag{5}$$

$$\eta_{II,CYCLE} = \frac{\sum \dot{W}_{NET,OUT} + \sum \dot{X}_{STEAM,OUT}}{\dot{X}_{FUEL}} \tag{6}$$

For the financial analysis the first step is to quantify the initial investment of the plant and the monthly cash flow (equation 7). With both values it is possible to determine the NPV (net present value, equation 8) and the IRR (internal rate of return, the zero of equation 9). The NPV quantifies the present value of the net dividends of the investment. In other words how many dollars the investment will generate in its whole life. The IRR compares the investment in the plant with a virtual one in the financial market, e.g., if the IRR of the plant is 10% this signifies the investment on the plant is financially equivalent to an investment of 10% on the financial market. The NPV gives absolute figures in dollars and the IRR gives percentage gains.

$$CF(j) = \sum_{j=0}^{N} entries\,(j) - \sum_{j=0}^{N} spendings\,(j) \tag{7}$$

$$NVP = Initial\ investiment + \sum_{j=0}^{N} \frac{CF(j)}{(1+i)^j} \tag{8}$$

$$\sum_{j=0}^{N} \frac{CF(j)}{(1+IRR)^j} + Initial\ investiment = 0 \tag{9}$$

The first study performed was the behavior of the plant on off-design conditions. Table 03 present the description of the cases considered. Case 1 is the base case, where the milling flux is 650 ton of sugar cane per hour, the backpressure turbine generates 50 MW of electricity and the condensing turbine generates 20 MW of electricity. In case 2, for example, the milling was reduced in 5% but the electricity was maintained on the same level. In cases 1-4 the milling (and consequently the necessity of steam) is reduced maintaining the electricity generation constant. In cases 5-7 the milling is set to a minimum, the backpressure turbine has its power continually diminished and the condensing turbine have its power continually increased. In cases 8-10 the milling is set to a minimum of 85%, the backpressure has its power continually increased and the condensing turbine its power continually decreased. In cases 11-13 the milling, backpressure and condensing turbine have all its power diminished. In cases 14-17 the power generated by the condensing turbine is maintained in 100% while both the milling and backpressure power are diminished. In cases 18-20 the power generated by the backpressure turbine is maintained in 100% while both the milling and condensing pressure are diminished.

The cases presented in table 3 were used on 3 different sets of simulations: set 1) using the nominal values of selling sugar/alcohol and electricity, set 2) considering that the selling value of alcohol/sugar had its selling price diminished by 20% while the selling price of electricity have its price increased by 20% and set 3) considering that the selling value of alcohol/sugar had its selling price increased by 20% while the selling price of electricity have its price diminished by 20%. The 3 set of cases are summarized in table 4.

Table 3. Description of the cases

Cases	Loads		
	Milling [%]	Backpressure Turbine[%]	Condensing Turbine[%]
1	100.0	100.0	100.0
2	95.0	100.0	100.0
3	90.0	100.0	100.0
4	85.0	100.0	100.0
5	85.0	95.0	112.5
6	85.0	90.0	125.0
7	85.0	85.0	137.5
8	85.0	104.0	90.0
9	85.0	108.0	80.0
10	85.0	112.0	70.0
11	95.0	95.0	95.0
12	90.0	90.0	90.0
13	85.0	85.0	85.0
14	100.0	100.0	100.0
15	95.0	95.0	100.0
16	90.0	90.0	100.0
17	85.0	85.0	100.0
18	95.0	100.0	95.0
19	90.0	100.0	90.0
20	85.0	100.0	85.0

Table 4. Description of the change in the set of cases

SET Cases	Price	
	Steam	Eletric Energy
Set 1	Market (Estimated by alcohol and sugar)	Market [01]
Set 2	20% minus of market	20% plus of market
Set 3	20% plus of market	20% minus of market

[01] Market price of energy (R$170,00/MW)

It should be stressed there is no technical variation on a specific case when the selling values are varied. The difference between the sets is only financial. By this reason only the efficiencies of set 1 are shown on figure 2 as the other sets would present exactly the same values. Figure 2 shows the energetic and exergetic efficiencies for the 20 studied cases. The first important result is both efficiencies have the same qualitative behavior. The base case remains the best case on a efficiency comparison despite the variations on the loads showing great robustness. There is a tendency for an increase on the efficiency when the proportion of steam diverted to the condensing turbine. Finally other result seen in figure 2 is that cases 4 and 10 present low efficiencies because the steam passing trough the backpressure turbine is not been used on milling or alcohol/sugar production.

Figures 3, 4 and 5 show the financial indexes for the 3 sets of cases. In the 3 graphs can be seen that the NPV and IRR have qualitatively the same behavior. This allows the conclusion that either NPV or IRR can be use solely for the optimization.

In figure 6 it is presented a comparison between the NPV of the set of data. It is clear that changes on the selling values change quantitatively the behavior of the NPV but qualitatively the behavior is exactly the same. Another important result to be noticed in figure 6 is the preference for an increase of the selling value of electricity.

Finally on figure 7 it is possible to see that the qualitative behavior of the financial and technical indexes is almost the same. This is an important result because points to the use of only technical indexes for the first scenario choice in the beginning of the design. Moreover there are two important exceptions: cases 10 and 18, that do not present the same behavior. Those exceptions points to a great care that should be taken on the use of only technical indexes as optimization parameters.

It's important to notice that additional fuel is purchased when that quantity of steam passing through the turbines is greater than the milling capacity to produce that steam. In the case of excess steam, there is a bypass system not shown in Figure 1.

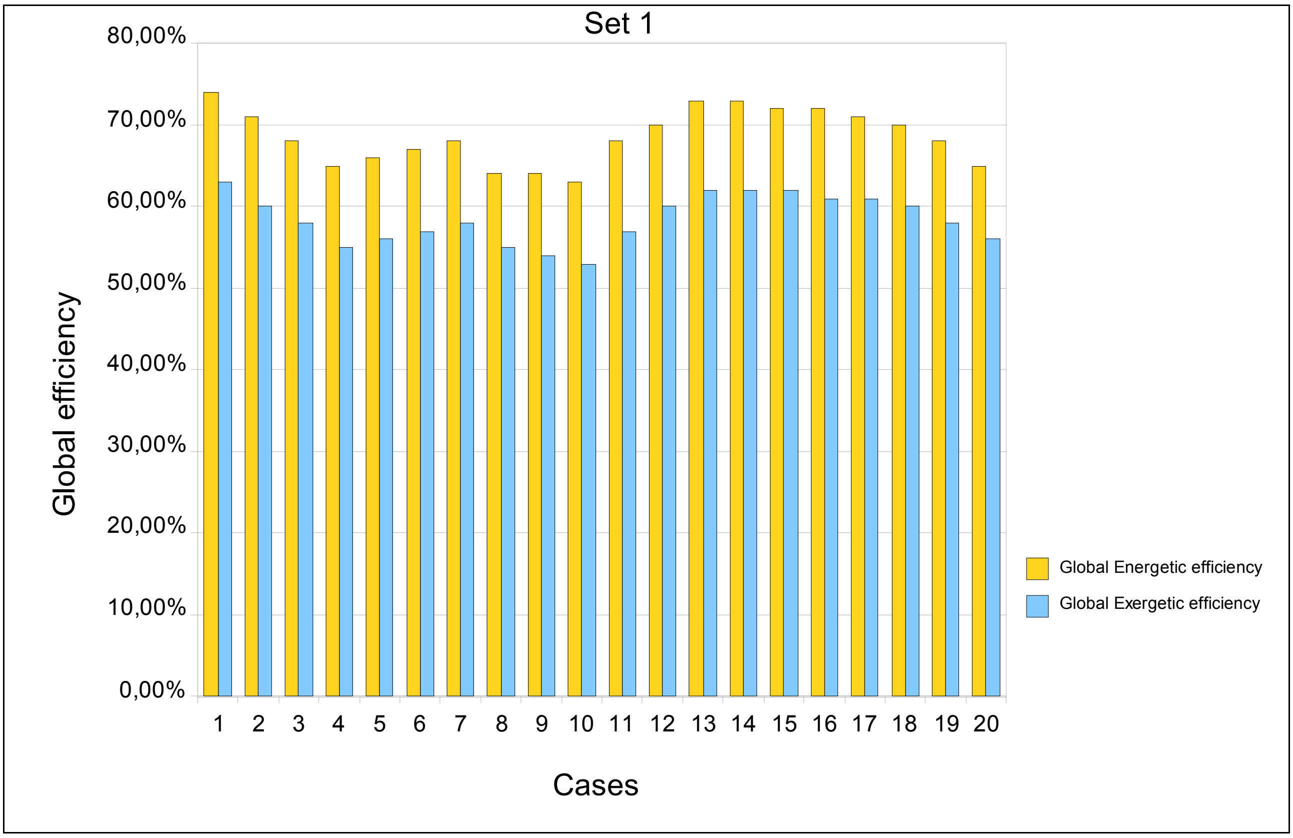

Figure 2- Efficiencies for set 1. [Efficiency is defined by the ratio between the delivered energy (mechanical plus steam for the process) and the energy of the fuel]

Figure 3. NPV and IRR for set 1.

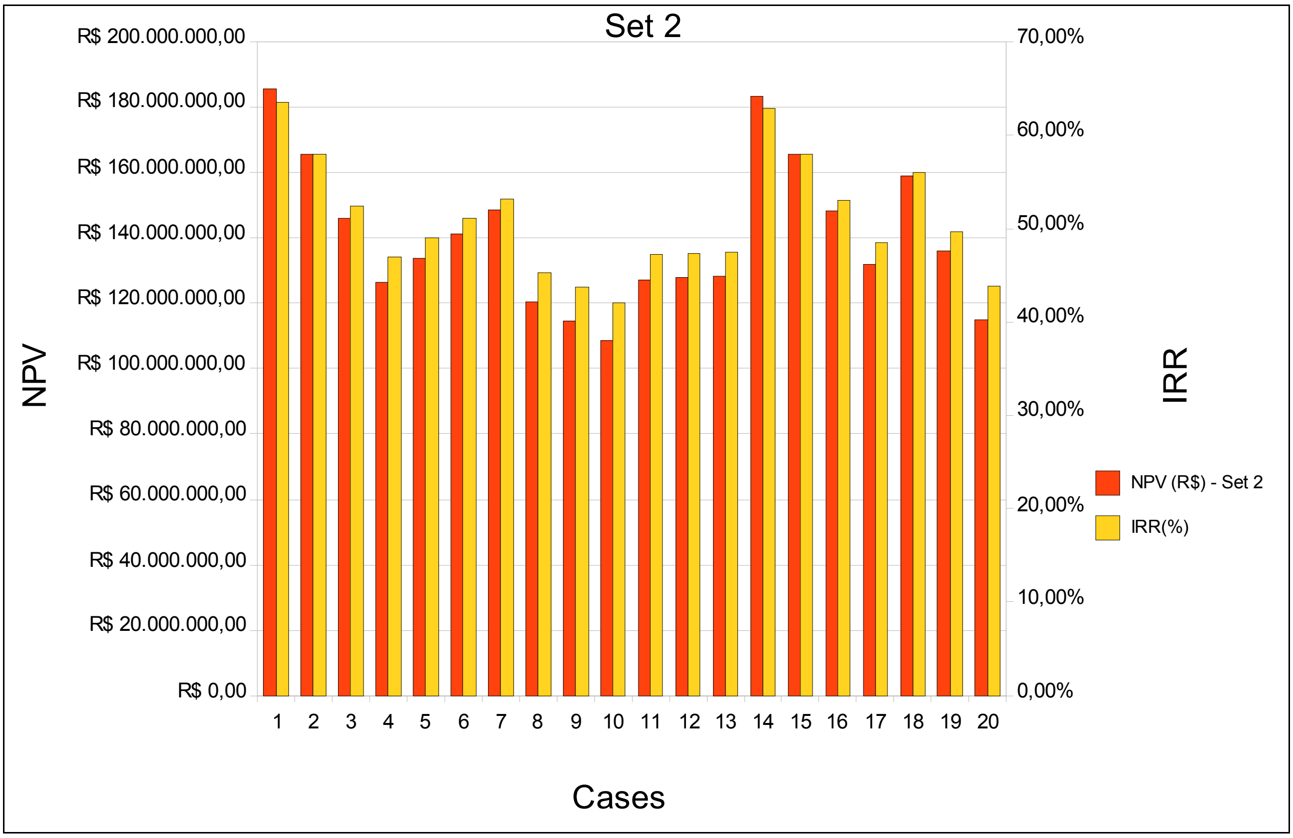

Figure 4 - NPV and IRR for set 2.

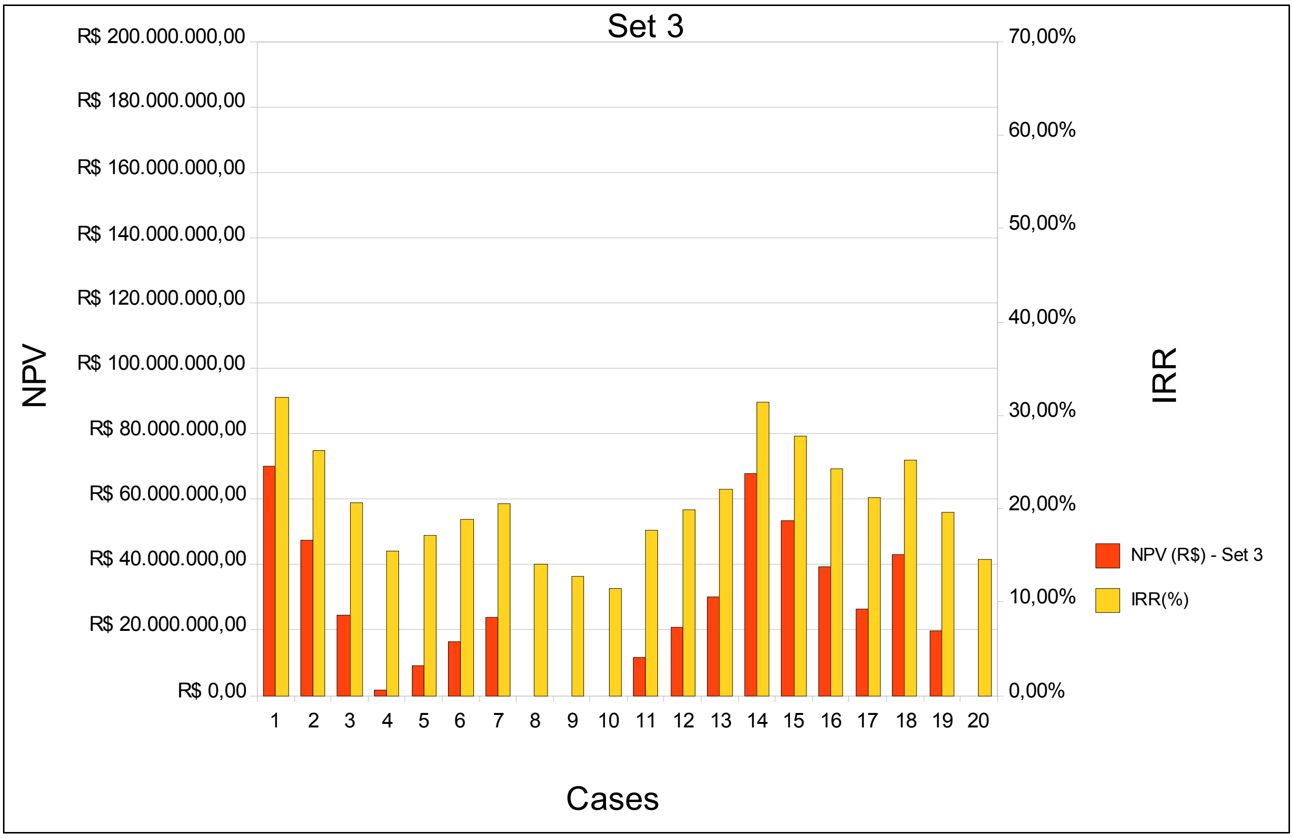

Figure 5 - NPV and IRR for set 3.

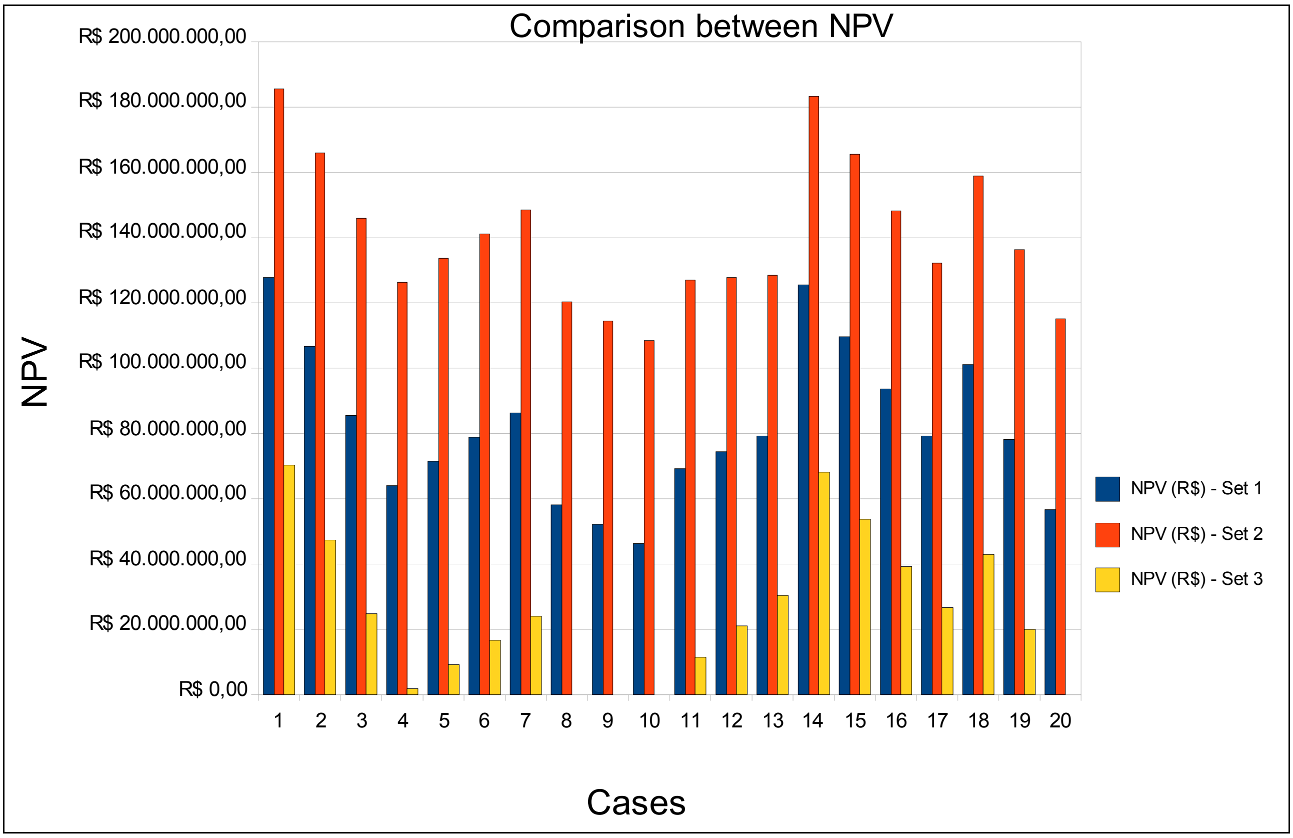

Figure 6 - Comparison between NPV between the sets of data.

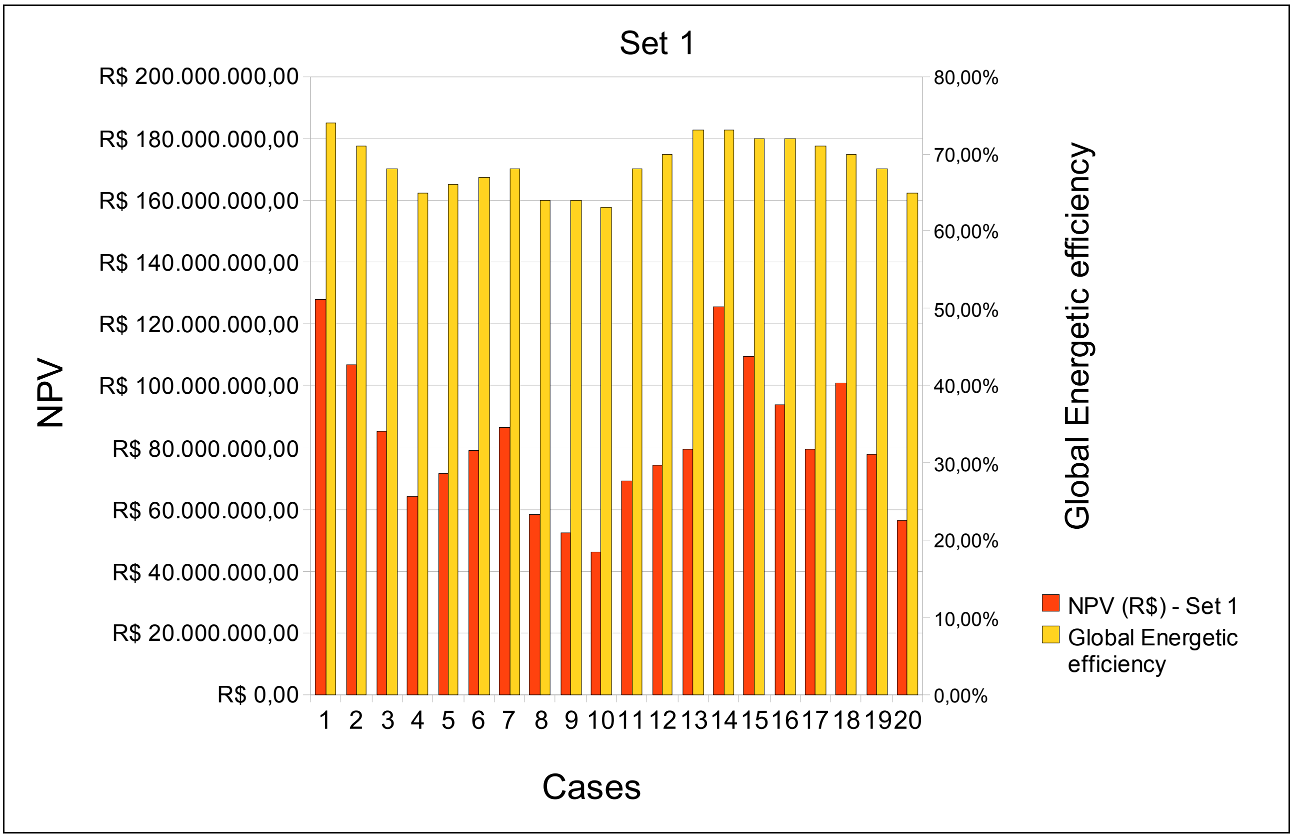

Figure 7 - Comparison between NPV and energetic efficiency for set 1.

4. CONCLUSIONS

A 70 MW cogeneration plant was studied. It was varied its loads and selling values of its products (electricity, sugar and alcohol).

Very important results was reached, but it would never be enough to stress that those conclusions are valid only for this plant and this range of variation. The first conclusion was the technical indexes - the energetic and exergetic efficiencies - have tha same qualitative behavior. The same stands between the financial indexes NPV and IRR. Additionally the technical and financial indexes have almost the same qualitative behavior with two important exceptions. Those results points to the use of the technical indexes alone on the very beginning of the design processes in the choice of the scenarios but also to the mandatory use of the financial indexes on the optimizing processes. Other conclusion is that the base case is very robust. Despite the variation on the loads and selling values, the base case remained the best one. Finally, two results point to the extensive use of alcohol and sugar plants on the electricity selling: the higher sensibility of the NPV on the selling value of electricity and the tendency of rising of efficiency and NPV as the flux to the condensing turbine is increased.

Future research should extend the studies to learn in what range the financial and technical indexes remains with the same behavior. The same study should be done about the similarity as optimization parameters of the energetic and exergetic efficiencies.

5. ACKNOWLEDGEMENTS

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