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**NUMERICAL OPTIMIZATION OF A COGENERATION SYSTEM IN A  
SUGAR AND ALCOHOL PLANT**

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**Abstract.** *This work aims the numerical analysis from the thermodynamic point of view of a power generation plant in a sugar-energy plant using the IPSEpro<sup>®</sup> software, calculating parameters such as efficiency, thermal energy, power, among others. Two cases were evaluated in which there was a variation in the production mix of the plant and, by using the genetic algorithm solution method, an optimization procedure was performed to identify optimal operating configurations that maximize power generation, meeting the demand for thermal energy. The optimization generated an improvement in power generation in the two cases studied. The optimization indicated that when the intake flow of the extraction-condensation turbine reaches its maximum capacity and the rest of the available steam directed to the second turbine, the process is more efficient. The optimum condensation values of the turbine indicated by the optimization are those close to the lower limit of the operating range of the turbine chart.*

**Keywords:** sugarcane, renewable energy, optimization.

## 1. INTRODUCTION

The population increase and the acceleration of human activity provoke a scenario of increased consumption of energy, especially fossil fuels, which causes an increase in GHG (Green House Gases) rates, mainly of carbon dioxide (CO<sub>2</sub>). This fact is alarming due that fossil fuels contribute about 80 to 95% of the world's electricity demand. This dependence leads to the depletion of natural resources. Therefore, it is necessary to find new energy sources for economic growth without damaging the environment (Said and Omri, 2020).

Biomass is an example of an interesting alternative due to the fact that plants use photosynthesis to convert solar energy into chemical energy and his renewable energy is converted into biofuels (Demirbas, 2010). A widely used example of biomass is sugarcane that has one of the highest efficiencies of bioconversion, which in Brazil it is used in the production of sugar and ethanol (anhydrous and hydrated). Sugarcane bagasse, a residue of this production, is used in the simultaneous production of heat and electric energy (cogeneration process) for use by the plants themselves, being the excess of electrical energy exported to the network (Carvalho et al., 2020).

Brazil is considered the largest producer of sugarcane in the world, with 746.8 million tons produced in 2018, which represents 39.16% of world production (FAO, 2019). In sugar and ethanol plants, the steam generated by the boilers feeds the turbo generators, where mechanical energy is transformed into electrical energy. Furthermore, different processes of sugar and alcohol use steam, like broth treatment, evaporation, distillation and cooking (Perez et al., 2018).

There are several proposals to improve efficiency in the production of electrical energy and heat in sugar and ethanol plants, such as increasing the parameters of the steam cycle, the electric drive of the plants, integrated biomass gasification systems and reducing the consumption of steam in the processes.

Optimization is a subject that has generated many studies and engineers' attention to generate high efficiencies and lower production costs for systems. There are several computational methods capable of solving the most diverse and complex optimization problems. Cremones (2013) carried out different simulations for the operation of a sugarcane mill that produces sugar, ethanol and bioelectricity, which requiring the purchase of bagasse to meet energy sales contracts. For this, it was taking into account the variations in the milling (from 1,500,000 to 1,800,000 tons of cane by harvest) and in the sugar-alcohol production mix (from 40 to 80 %). Fonseca et al. (2017) optimized a system to determine the ideal sugarcane biomass fractions that should be used for the production of cellulosic ethanol, as a fuel in the generation of steam for a Rankine Combined Cycle

or be fed to the Integrated Gasification Combined Cycle Biomass. The objective was to maximize the Net Present Value (NPV) to determine which of the combined cycles is most economical. Pellegrini and Oliveira Junior (2011) performed an exergetic optimization of cogeneration systems in sugar plants. A discussion has been carried out about the variables that most affect the performance of the processes and a procedure was presented to assess changes in the cogeneration system and the process and their impact on the costs of producing sugar, ethanol and electricity.

Overall, the main goal of the present work is to optimize a power generation plant in a sugarcane plant using the IPSEpro<sup>®</sup> software, evaluating cases in which there was variation in the sugar-ethanol production mix. The plant is essentially composed of a boiler and two turbines, one of which is extraction-condensation (32 MW) and one of back pressure (15 MW). The turbines produce steam that feed the plant's production process and electricity. The value of the production mix directly affects the amount of steam required to meet the needs of the process.

## 2. METHODOLOGY

### 2.1 System description

Figure 1 shows the power plant configuration for the generation, distribution and consumption of steam from a sugar-ethanol plant considered for all analyzes.

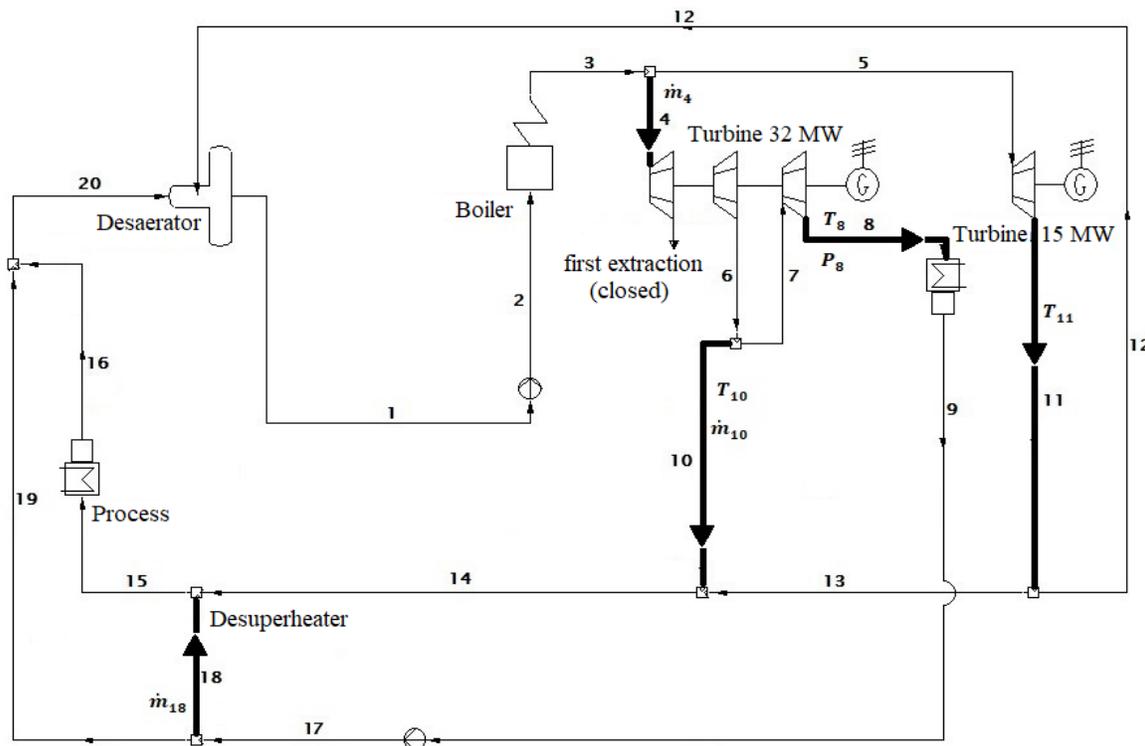


Figure 1. Cogeneration system of a sugar-alcohol plant.

In this plant, all steam produced in the boiler is distributed between the 32 MW condensing extraction turbo generator and a 15 MW backpressure turbo generator for the additional production of electricity. Although the 32 MW turbo generator has three steam output options, in our studies, the first extraction is closed. The steam extracted in the second extraction of the turbo generator and the exhaust steam in the backpressure turbine, both at 245 kPa and 159.7 °C, go to the desuperheater (located between points 14 and 15), where they receive a controlled injection of water so that the temperature remains at approximately 135 °C. Subsequently, the steam that leaves the desuperheater is used in the process of evaporation of the broth (represented by a condenser located between points 15 and 16). During the process, the steam is condensed and the water is pumped to the deaerator. Then, the water is pumped back into the boiler and the cycle begins again.

### 2.2 Optimization Problem

The power plant presented was submitted to the Genetic Algorithm optimization method, already implemented in the IPSEpro<sup>®</sup> software. The objective function is to maximize the power generation in the two turbines ( $\dot{W}$ ) and, consequently, the efficiency of the plant. The optimization declaration, according to suggested by Rao (2019), can be described for that particular case according to Equation (1):

$$\text{Find } X = \begin{Bmatrix} \dot{m}_{18} \\ \dot{m}_{10} \\ \dot{m}_4 \\ T_{10} \\ T_{11} \\ P_8 \\ T_8 \end{Bmatrix}, \text{ that maximizes } \dot{W}_{32MW} + \dot{W}_{15MW} \quad (1)$$

subject to the following restrictions:

$$\text{Process inlet temperature (Point 15): } T_{process} \geq 135^\circ\text{C} \quad (2)$$

$$\text{Flow of steam for the process (Point 15): } \dot{Q}_{process} \geq 33.87, \text{ for mix 40\%} \quad (3)$$

$$\dot{Q}_{process} \geq 36.16, \text{ for mix 50\%} \quad (4)$$

$$\dot{Q}_{process} \geq 38.92, \text{ for mix 60\%} \quad (5)$$

$$\dot{Q}_{process} \geq 36.16, \text{ for mix 70\%} \quad (6)$$

$$\dot{Q}_{process} \geq 43.83, \text{ for mix 80\%} \quad (7)$$

The decision variables and their ranges are shown in Table 1. The data were based on the real operating conditions of a plant located at São Paulo State, according to the points shown in Figure 1.

Table 1. Parameters used during optimization procedure.

Decision variable	Range
Condensing flow fraction of Turbine 32 MW to the desuperheater ( $\dot{m}_{18}$ )	0 – 100 %
Mass flow extraction at Turbine 32 MW ( $\dot{m}_{10}$ )	17 – 35 kg/s
Inlet flow at Turbine 32 MW ( $\dot{m}_4$ )	0 – 38.88 kg/s
Extraction temperature at Turbine 32 MW ( $T_{10}$ )	134.5 – 200 °C
Outlet temperature at Turbine 15 MW ( $T_{11}$ )	126.0 – 200 °C
Condensing outlet pressure at Turbine 32 MW ( $P_8$ )	0.055 – 0.115 bar
Condensation outlet temperature at Turbine 15 MW ( $T_8$ )	34.6 – 48.60 °C

To define the number of generations and the size of the population, as well as the mutation and crossover rates, tests were carried out with the same plant, in which the values of these variables were changed and evaluated in detail. The behavior of the objective function was monitored until the solution is converged. Finally, the values chosen for the tests were 100 for the population and 80 for the number of generations. Moreover, the final value of the probability of crossover and mutation were both 0.9.

## 2.2 Case 1. Production Mix

For the simulations, five production conditions are used in which the mix between sugar/ethanol from the plant (percentage of total recoverable sugar available that will be transformed into sugar or ethanol) varies between 40 – 80%. The greater the sugar production, the greater the amount of steam required in the production process that must be met by the power plant.

Table 2 presents the data for the simulations, taken from Cremonex (2013), related to real operational data from the same plant considered in this work. The data refer to the amount of steam needed to meet the process according to the production mix applied.

Table 2. Parameters used during optimizations.

Production Mix (%)	Quantity of steam required (kg/s)
40	33.9
50	36.2
60	38.9
70	41.2
80	43.8

### 2.3 Case 2: Production mix for several total mass of the system

For an increase in the demand for steam due to the need of the process, it is natural that the steam is available for the production of electrical energy to decrease. In this way, a situation was simulated in which more bagasse is burned in the boiler to compensate the extra amount of steam that is used in the process according to the mix of production. This is possible since there is usually a surplus that is not totally consumed by the plant.

In this analysis, the total mass flow of the system was increased to the value corresponding to the increase in the steam demand for process in all cases of the production mix. This was done, in order to prevent significant decreases in the total electrical energy production due to the increase of steam used in the process. Table 3 shows the amount of steam required by the process and the total mass flow of steam from the system in each configuration.

Table 3. Process steam and total mass flow of the system according to the production mix.

Production Mix (%)	Quantity of steam required (kg/s)	Total mass flow of the system (kg/s)
40	33.9	58.3
50	36.2	60.6
60	38.9	63.4
70	41.2	65.7
80	43.8	68.3

## 3. RESULTS

Table 4 presents the results of the base case for mix of 40%. For the other production mix values, the demand for process steam and the total mass flow of the system, in Case 2, is altered by those presented in Table 3. To achieve these values while preserving the original plant values as much as possible, it was necessary to change the extraction value of Turbine 32 MW. In this case, as there is a lower limit in the extraction-condensation turbine extraction, and the demand for process steam is around 34 kg/s, there was a small surplus of process steam (Point 15). This shows that the plant in this configuration does not reach its maximum generation capacity, where all the excess steam would be expanded in the turbines to generate electricity. The energy generated by the extraction-condensation turbine (Turbine 32 MW), the backpressure turbine (Turbine 15 MW) and the total generation were: 24.4 MW, 14.1 MW and 38.5 MW, respectively.

Table 4. Thermodynamic analysis of the base case.

Point	<i>P</i> (bar)	<i>T</i> (°C)	$\dot{m}$ (kg/s)	<i>h</i> (kJ/kg)	<i>s</i> (kJ/kg·K)	<i>v</i> (m <sup>3</sup> /kg)
1	2.45	126.8	58.33	532.52	1.60	0.001067
2	78.60	128.1	58.33	543.37	1.61	0.001064
3	68.60	530.0	58.33	3,485.09	6.90	0.05154
4	68.60	530.0	34.72	3,485.09	6.90	0.05154
5	68.60	530.0	23.61	3,485.09	6.90	0.05154
6	2.45	159.7	34.72	2,785.90	7.23	0.799
7	2.45	159.7	19.72	2,785.90	7.23	0.799
8	0.070	39.6	19.72	2,572.91	8.28	20.56
9	0.070	39,0	19.72	163.32	0.56	0.001
10	2.45	159.7	15.00	2,785.90	7.23	0.799
11	2.45	159.7	23.61	2,785.90	7.23	0.799
12	2.45	159.7	3.45	2,785.90	7.23	0.799
13	2.45	159.7	20.15	2,785.90	7.23	0.799
14	2.45	159.7	35.15	2,785.90	7.23	0.799
15	2.45	136.0	35.83	2,735.71	7.11	0.752
16	2.45	121.8	35.83	511.25	1.55	0.001
17	2.45	39.0	19.72	163.63	0.56	0.001
18	2.45	39.0-	0.68	163.63	0.60	0.001
19	2.45	39,0	19.04	163.63	0.56	0.001
20	2.45	108.8	54.87	44.65	1.41	0.001

### 3.1 Optimization results for Case 1

Table 5 presents the values of the parameters that were optimized in Case 1 considering the production mix and the data obtained in point 15 (process).

Table 5. Optimization results for Case 1.

Mix (%)	Parameter	Turbine 32 MW			Turbine 15 MW		Process	Power (MW)		
		Inlet (Point 4)	2 <sup>nd</sup> Extraction (Point 10)	Condensation (Point 8)	Inlet (Point 5)	Outlet (Point 11)	Inlet (Point 15)	$\dot{W}_{32MW}$	$\dot{W}_{15MW}$	$\dot{W}_{total}$
40	<i>P</i> (bar)	68.6	2.45	0.0552*	68.6	2.45	2.45	26.87*	12.08*	38.95*
	<i>T</i> (°C)	529.99	152.73*	35.15*	529.99	163.72*	135.35*			
	$\dot{m}$ (kg/s)	37.96*	17.07*	20.89*	20.36*	20.36*	34.25*			
50	<i>P</i> (bar)	68.6	2.45	0.0621*	68.6	2.45	2.45	26.67*	12.05*	38.72*
	<i>T</i> (°C)	529.99	146.31*	38.61*	529.99	164.59*	135.21*			
	$\dot{m}$ (kg/s)	37.96*	18.84*	19.12*	20.36*	20.36*	36.33*			
60	<i>P</i> (bar)	68.6	2.45	0.055*	68.6	2.45	2.45	26.62*	11.79*	38.41*
	<i>T</i> (°C)	529.99	144.00*	36.85*	529.99	163.73*	137.00*			
	$\dot{m}$ (kg/s)	38.42*	22.29*	16.13*	19.91*	19.91*	39.63*			
70	<i>P</i> (bar)	68.6	2.45	0.0555*	68.6	2.45	2.45	26.37*	12.12*	38,49*
	<i>T</i> (°C)	529.99	145.03*	35.42*	529.99	153.86*	135.17*			
	$\dot{m}$ (kg/s)	38.42*	23.78*	14.64*	19.91*	19.91*	41.31*			
80	<i>P</i> (bar)	68.6	2.45	0.0550*	68.6	2.45	2.45	26.29*	11.91*	38.20*
	<i>T</i> (°C)	529.99	144.77*	35.04	529.99	151.83*	135.17*			
	$\dot{m}$ (kg/s)	38.88*	26.60*	12.28*	19.45*	19.45*	44.03*			

\* values changed due to optimization procedure.

These results show a decrease in the total electric energy generated by the turbines as the production mix increased. This is due to the system needing more energy to meet the demands of the process, which caused an increase in the extraction of the extraction-condensation turbine (Turbine 32 MW) and, therefore, a decrease in the production of electrical energy. This can be seen in the increase in steam flow in the 2nd extraction ( $\dot{m}_{10}$ ), which goes from 11.07 kg/s for mix 40% to 26.60 kg/s for mix 80%.

The optimization indicated that the optimum point occurs when the flow of the extraction-condensation turbine ( $\dot{m}_4$ ) is taken to the end of its operational range (38.88 kg/s), while the remainder of the steam produced from the burning of the bagasse is directed to the backpressure turbine (Turbine 15 MW). In this way, for all cases, a similar division of steam occurs between the two turbines.

It is also possible to observe that the increase in power generation due to optimization was 0.82% for mix 50% and reached 2.68% for mix 80%. This increase is due to the outlet temperatures of the turbines, which in the base cases were 159.7 °C for the two turbines.

The results of the optimization indicated values in the range of 146 °C for the outlet temperature of the Turbine 32 MW, which added to the increase in steam inlet flow (which in the base case was 34.72 kg/s) explains the increase generation of electricity related to the base case. For the Turbine 15 MW, the optimization procedure indicated an average outlet temperature of 164°C for mix 40, 50 and 60% and 152.8°C for mix 70 and 80%. This difference in the outlet temperature of the Turbine 15 MW explains the increase in the last cases was more significant.

Moreover, the optimization procedure indicated a condensation pressure of the extraction-condensation turbine (Turbine 32 MW) close to the lower limit of the operating range for all cases. The same happened with the condensation temperature, which had an average value of 36.21°C. The mass flow  $\dot{m}_{18}$  had decreasing values as the production mix increased, from 0.61 kg/s for mix 40% and reaching 0.44 for mix 80%.

### 3.2 Optimization results for Case 2

Table 6 presents the results for optimization procedure for the Case 2, in which the total mass flow of the system was increased by the value corresponding to the increased demand for process steam for all production mix.

Table 6. Optimization results for Case 2 (Production mix with several total mass of the system).

Mix (%)	Parameter	Turbine 32 MW			Turbine 15 MW		Process	Power (MW)		
		Inlet (Point 4)	2 <sup>nd</sup> Extraction (Point 10)	Condensation (Point 8)	Inlet (Point 5)	Outlet (Point 11)	Inlet (Point 15)	$\dot{W}_{32MW}$	$\dot{W}_{15MW}$	$\dot{W}_{total}$
40	P (bar)	68.6	2.45	0.0552*	68.6	2.45	2.45	26.87*	12.08*	38.95*
	T (°C)	529.99	152.73*	35.15*	529.99	163.72*	135.35*			
	$\dot{m}$ (kg/s)	37.96*	17.07*	20.89*	20.36*	20.36*	34.25*			
50	P (bar)	68.6	2.45	0.055*	68.6	2.45	2.45	27.53*	12.89*	40.42*
	T (°C)	529.99	147.85*	34.93*	529.99	166.05*	135.35*			
	$\dot{m}$ (kg/s)	38.73*	17.66*	21.07*	21.88*	21.88*	36.32*			
60	P (bar)	68.6	2.45	0.0564*	68.6	2.45	2.45	27.59*	14.64*	42.23*
	T (°C)	529.99	149.39*	35.31*	529.99	159.95*	135.20*			
	$\dot{m}$ (kg/s)	38.88*	17.63*	21.24*	24.49*	24.49*	38.86*			
70	P (bar)	68.6	2.45	0.0557*	68.6	2.45	2.45	27.74*	15.91*	43.65*
	T (°C)	529.99	144.00*	34.82*	529.99	163.43*	135.86*			
	$\dot{m}$ (kg/s)	38.88*	17.92*	20.96*	26.79*	26.79*	41.45*			
80	P (bar)	68.6	2.45	0.0585*	68.6	2.45	2.45	27.53*	17.86*	45.39*
	T (°C)	529.99	150.93*	36.03*	529.99	154.43*	135.26*			
	$\dot{m}$ (kg/s)	38.88*	17.56*	21.31*	29.4*	29.40*	43.65*			

\*values changed due to optimization procedure.

Although the plant needs a lot of amount of the steam generated to attend to the process needs, there was an increase in the total energy produced as the production mix increased. This is due to the first turbine has a maximum inlet flow capacity of 38.88 kg/s, which causes the need for this excess steam produced by the boiler to be expanded by the back-pressure turbine (Turbine 15 MW), which has most of its exhaust steam directed for the process, meeting the need for steam. This fact implied a steam flow in the second extraction of Turbine 32 MW almost constant ( $\dot{m}_{10}$ ).

The conditions of inlet and outlet of Turbine 32 MW remained slightly constant from one case to the other, however, the power generation still increased as the production mix increased. Therefore, the increase in steam process demand added to the increase in produced steam promotes an increase in power generation from the turbines.

The average outlet temperature for Turbine 32 MW was 148.9°C and for Turbine 15 MW it was 163.3°C for the mix 40, 50, 60 and 70% and 154.4°C for mix 80%. These results imply an increase in the power generation of the Turbine 32 MW related to the base case and a decrease in the generation of the Turbine 15 MW.

Regarding the condensation of the extraction-condensation turbine, the optimization indicated an average outlet pressure of 0.056 bar and an average outlet temperature of 35.2°C, values that are close to the minimum extremes of the turbine's operating range.

In this case, the optimization results indicated for the steam inlet flow distribution for the two turbines for all cases maximum inlet flow (38.88 kg/s) for Turbine 32 MW, with the remainder steam produced by the boiler conducted to the Turbine 15 MW. It is also important to notice that in the last two cases the electric power generation of the second turbine exceeded the maximum nominal value (15 MW), as there was no generation limitation (restriction) during the optimization procedure. For the Turbine 32 MW, generation remained below at the maximum value (32 MW), which is due to the second extraction of the condensation-condensation turbine, that is necessary to attend the process steam demand, but also prevents a full expansion available steam and a consequent greater generation of electrical energy.

### 3.3 Effect of optimization for electrical power generation

The results for the electrical generation are shown in Figure 2, where the red and the blue lines represent the results for the base case and the optimized cases, respectively.

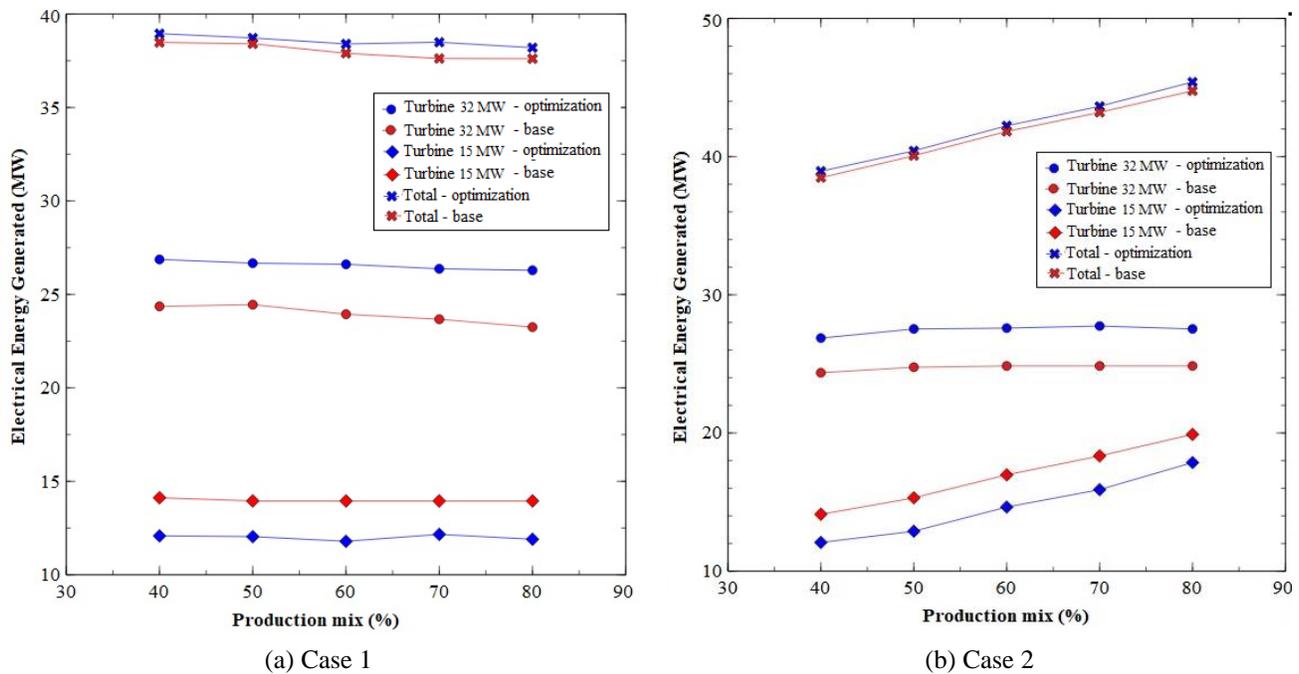


Figure 2. Variation of the energy generated according to the production mix for Cases 1 and 2.

From the Figure 2, it is possible to verify that for both cases the power generation of the first turbine increased compared to the base case, while the generation of the second turbine decreased. However, the total electricity generation increased for both cases due to optimization procedure, reaching 2.68% for the 80% mix for the Case 1 and 1.45% for the Case 2.

## 4. CONCLUSION

The optimization procedure found optimal operational conditions for both cases evaluated. The more steam coming from the boiler to the 15 MW turbine, the less steam is needed for the extraction-condensation turbine process. For both cases, the optimization procedure showed that it is an advantageous techniques to find optimal operational conditions under several

constraints. The optimization indicates that the best results occur when there is the lowest possible extraction value of the second turbine, as long as the demands of the production process are met. The optimum condensation values of the turbine indicated by the optimization are those close to the lower limit of the operating range of the turbine chart.

In addition, the optimizer has always indicated lower outlet temperatures for this turbine than for the second, which caused greater efficiencies and consequently greater energy generation. In the end, the improvement due to optimization was always more expressive in the extraction-condensation turbine.

Although the optimization indicates lower generation values for the back pressure turbine (15 MW) in relation to the base case, the total generation was still higher than the previous one.

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## 7. RESPONSIBILITY NOTICE

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