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## **ESTIMATION OF SUGARCANE-BAGASSE ECONOMICS IN A COGENERATION PLANT WITH THE ADDITION OF A CSP SYSTEM**

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**Abstract.** *The objective of this work was to calculate the quantity of bagasse saved in a sugar-alcohol plant with cogeneration from the implementation of a concentrated solar energy central tower system, without thermal storage, in the harvest period. The solar field would act in parallel to the boiler, both always supplying the plant's steam demand. The boiler load would vary depending on the solar radiation received. For this model, the SAM software was used, which for a solar field of 45 MW, provided data of a typical solar year, and the amount of heat generated in the solar field. In order to determine the mass flows in the solar field and in the boiler, their respective energy balances and the internal heat exchange ratios of the boiler were considered. The results showed that with the implantation of the solar field, there was a bagasse savings of about 27%, which would generate a stock nearby 77 thousand tons of bagasse, which is approximately 5.5 times more than the current safety stock of the plant, and could be used in the off-season. In addition, with this leftover of bagasse, the plant would solve the problem of the amount of bagasse generated being less than the demand of the turbines.*

**Keywords:** *CSP System, Sugarcane biomass, hybrid system, biomass saving*

### **1. INTRODUCTION**

Renewable energies are the energies coming from inexhaustible sources, either because they are present in great quantity, or because they regenerate in natural processes. Its main benefit is in the environmental aspect, where its use is associated with the reduction of greenhouse gas emissions (GHG) which occurs through the substitution of electricity based on fossil and conventional fuels. This replacement is made from the use of natural sources like sun, wind, water flow and biomass, which are converted into useful forms of energy (Fernández-González et al., 2018; Shahsavari and Akbari, 2018). In Brazil, these energies account for 43.5% of domestic production in 2016 (Brasil, 2017).

Solar energy is the most abundant renewable energy source. It is considered endless and is fundamental in sustainable energy generation, since there almost none GHG emissions, especially when compared with other sources (Gelsor et al., 2018; Shahsavari and Akbari, 2018). Concentrated solar power plants are composed of two main parts, the solar field and the power block. The solar field acts by concentrating the direct solar radiation by means of mirrors, generally between 400 and 1000°C. This radiation is transformed into thermal energy in the form of high temperature working fluid. This, in turn, coupled to the turbines and generators, manages to produce electricity. Overall, the generation of electricity in concentrated solar power (CSP) plants operates similarly to conventional thermoelectric plants, but fossil fuels are replaced by solar energy (Belgasim et al., 2018; Fichter et al., 2017; Shahsavari and Akbari, 2018).

The classification of CSP plants depends on the type of solar collector used. One of the common types of technology employed is the Solar Tower. In this type of system, a sequence of two-axis mirrors is organized in a circular way, around a tower. They are called heliostats and can track and reflect solar radiation to the top of a tower, creating a focal point. In it, a central receiver is installed, which converts the solar radiation into heat. The solar tower generally operates in the range of 500 to 1000 °C, and has a generation potential of 100 kW up to 100 MW (Belgasim et al., 2018; Buck and Schwarzbözl, 2018).

This type of technology can work with or without heat storage or with any steam or gas system that operates in a Rankine cycle (Fichter et al., 2017; Shahsavari and Akbari, 2018). A favorable point to the hybridization of CSP-type systems is that it can compensate for solar intermittence, which is one of the biggest challenges when you do not have a

storage system. The intermittence reduces the capacity of the solar plant by about 23% and its efficiency from 15 to 30% (Pramanik and Ravikrishna, 2017).

One possible hybridization scenario for this CSP system is the burning of biomass for the formation of steam, such as bagasse and sugarcane straw, which is already carried out in most sugar and ethanol plants. According to the Bulletin of the Sugarcane Industry Union (Unica), the installed capacity of sugarcane biomass in the country exceeds the power of the Belo Monte power plant (UNICA, 2018).

In this context, it is proposed the hybridization of the sugarcane biomass system with a CSP system, where in during the sun hours CSP would be employed, saving the biomass, which would be used in hours when there was no solar irradiation available. The main advantage of this arrangement is that it would share the same electricity generation infrastructure already existing in the plants, which would reduce implementation costs. In addition, these are two renewable, low-CO<sub>2</sub> sources, which would complement each other as a seasonal and intermittent source (Burin, E, 2015; Burin, E. K. et al., 2016; UNICA, 2018).

Therefore, the objective of this work is to estimate the amount of bagasse that would be saved by the implantation of a CSP tower and central system, without storage, in a power plant that produces electricity from sugarcane bagasse burning, using as a case study the Jalles Machado power plant, located in Goianésia – GO.

## 2. METODOLOGY

The Jalles Machado power plant operates in a cogeneration system of energy, in which the sugar cane bagasse is used to generate electricity from its burning. Nowadays the plant has a generating capacity of 52 MW, which serves to meet the internal demands of industrial processes and the rest is sold.

With the insertion of the central tower, the plant could operate with partial load of biomass and it would be possible to store the bagasse for periods of off-season. The combination of solar and cogeneration systems eliminates two problems: solar intermittence, since it would be guaranteed the generation of energy in periods without solar radiation, and the seasonality, since there would be stock of the bagasse to be used in periods outside the sugarcane harvest.

### 2.1 Electric power generation plant of the Jalles Machado plant

Currently, the plant has a generating capacity of 52 MW, which serves to meet the internal demands of the industrial processes and the rest is sold. With the insertion of the central tower, the plant could operate with partial load of biomass and it would be possible to store the bagasse for periods of off-season.

The electric power generation plant of the Jalles Machado Power Plant (Fig. 1) operates in a Rankine cycle, where water vapor is formed from the heat generated by the biomass burning in the boilers, and is expanded in two turbo generators, one of back pressure with a nominal capacity of 28 MW and a condensing capacity of 24 MW. The former is responsible for fueling the plant's industrial processes, and the latter is sold in its entirety to the grid.

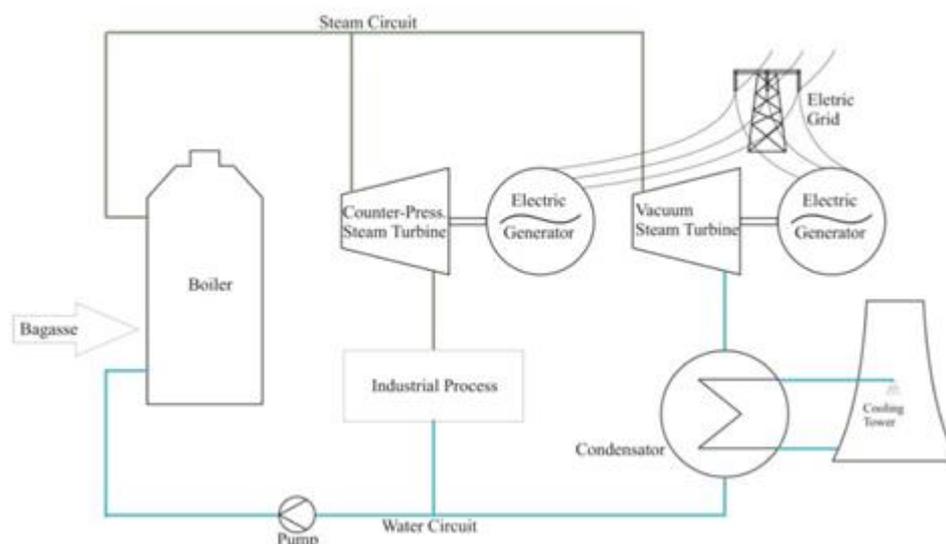


Figure 1. Current scheme of cogeneration of electricity in the Jalles Machado Power Plant

One of the problems that the plant has today is that to produce the nominal amount of electric energy, a quantity of steam is needed that is greater than that obtained by the burning of the available bagasse. The plant produces approximately 714 thousand tons of bagasse, of which it stores 2% in a safety stock.

The plant's boiler is of 1-pipe aqua tubular type, with nominal pressure and temperature of 65 bar and 490 °C, and a production capacity of 200 tons of steam per hour. It operates at 45 bar and 450 °C, exhibiting an efficiency of 81.5%. As the load on the boiler is reduced, its efficiency tends to decrease. It was considered that the greatest impact of this efficiency reduction would occur on the boiler superheater, because with the load reduction, the heat exchange coefficients also decreased. Taking this into account, a curve was made that relates the boiler load to its efficiency (Fig. 2).

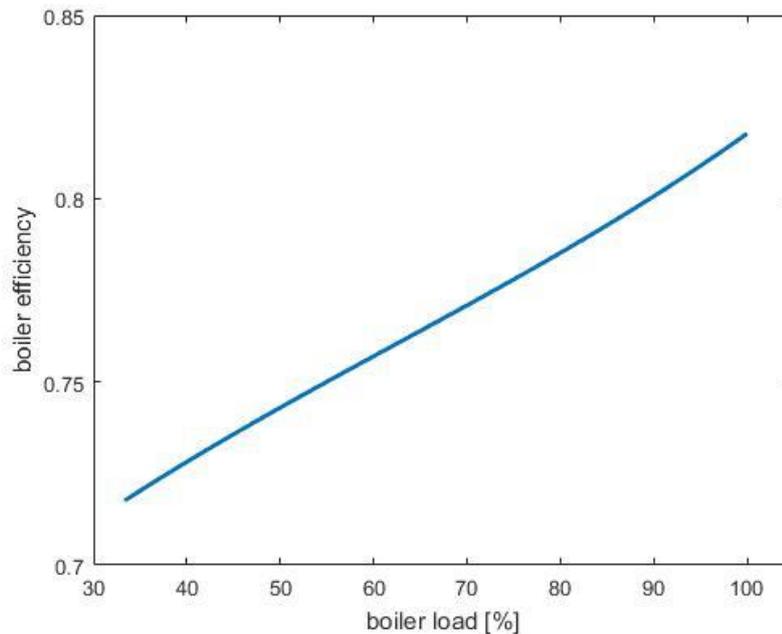


Figure 2. Relation between the efficiency of the boiler and the decrease in load

Based on the work of Almeida (2018) a minimum load of 30% was stipulated for boiler operation. With this value, it operates with an efficiency of 72%. This loss of efficiency in the boiler is due to some factors: constant volume of the boiler, with the decrease of the temperature due to the reduction of the bagasse burning; reduction of heat exchange by radiation; reduction of the flue gas velocity, which cause the reduction of heat transfer coefficients; incomplete combustion of the fuel (Almeida, 2018; Galante, 2015).

## 2.2 Hybrid system CSP + biomass

For the modeling of the heliothermic system, it was considered a central tower type solar collector plant with no thermal storage system and operating parallel to the boiler (Fig. 3). This arrangement has two main blocks: one composed by the solar field with the collectors, and another composed by the power generation block. The last one is the very system of electric generation that the plant already has, consisting of the turbo-generators and boiler.

The solar field was modeled using the System Advisor Model (SAM), a software developed by the National Renewable Energy Laboratory (NREL) designed for studies of renewable resource (Rodrigues and Siqueira, 2015), which provided the typical meteorological year (TMY) with the DNI, and the steam power generated at the tower receiver. The solar field was modeled from the data of the solarimetric station nearby Brasília. From the solar field's steam generation capacity and the steam demand at the plant, the amount of sugarcane bagasse that was saved was calculated, with the boiler operating continuously with load variation. This bagasse economy will be realized during the sugarcane harvesting period, which occurs between April and October. Thus, the stored cane can be used in the off-season, without affecting the direct generation of electric energy.

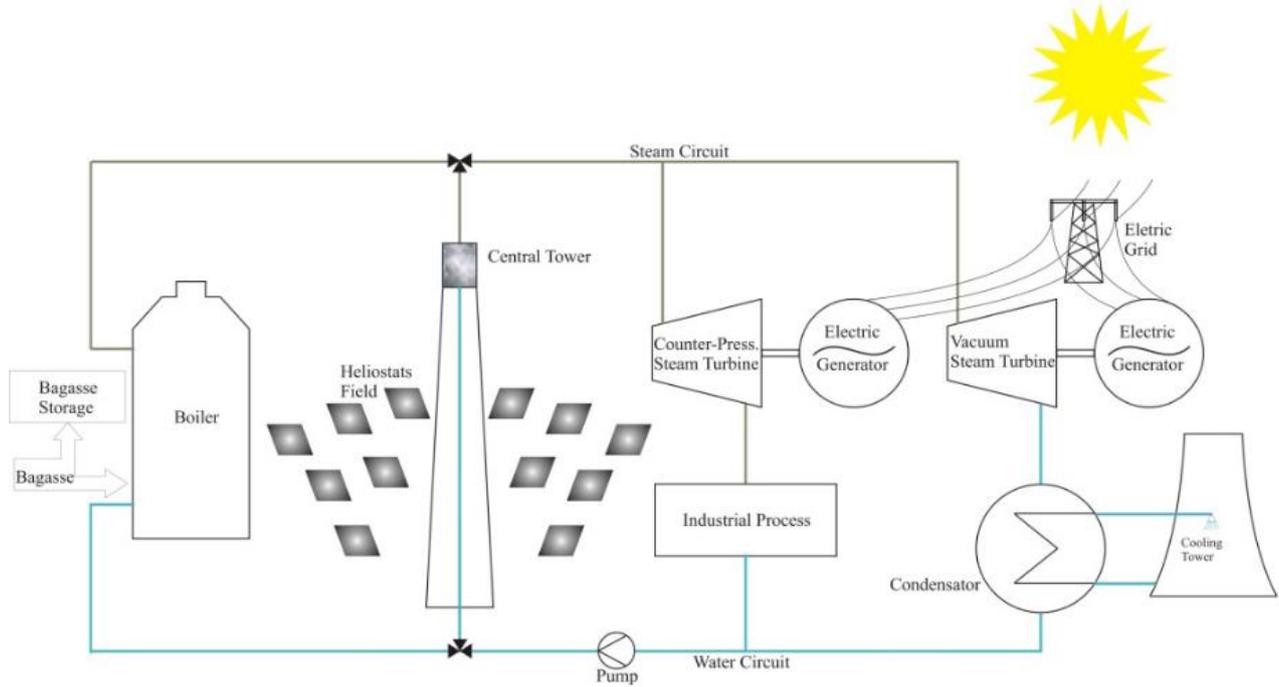


Figure 3. Scheme of hybridization of the plant with the CSP system of the central tower type.

To determine the required load at each period of the day, it was considered that the heat that the boiler supplies to the system ( $Q_{boiler}$ ) consists of two types of heat: one from the steam generation ( $Q_{SG}$ ) and the other from the superheater ( $Q_{SH}$ ), so that:

$$\dot{Q}_{boiler} = \dot{Q}_{SG} + \dot{Q}_{SH} \quad (1)$$

It was still considered that the load variation would only affect the  $Q_{SH}$ , since there would be convective losses due to the decrease of the heat transfer coefficients. With this, the mass and energy balance were carried out for the steam generating part, for the superheater and for the boiler as a whole:

$$\dot{Q}_{SG} = \dot{m}_{boiler}(h_s - h_{in}) \quad (2)$$

$$\dot{Q}_{SH} = \dot{m}_{boiler}(h_{out,boiler} - h_s) \quad (3)$$

Where,  $\dot{m}_{boiler}$  is the vapor mass flow of the boiler in kg/s;  $h_s$  is the enthalpy of steam formed, operating at boiler pressure, in kJ/kg;  $h_{in}$  is the enthalpy of boiler feed water, in kJ/kg;  $h_{out,boiler}$  is the enthalpy at the output of the boiler, in kJ/kg.

For heat generated in the superheater, the heat transfer rate was also considered:

$$\dot{Q}_{SH} = UA(T_{out,boiler} - T_s) \quad (4)$$

Where,  $U$  is the super-heater global heat-transfer coefficient, in  $W/m^2K$ ;  $A$  is the total area of the heat exchanger, in  $m^2$ ;  $T_{out,boiler}$  is the boiler outlet temperature, in  $^{\circ}C$ ;  $T_s$  is the saturated steam temperature, operating at boiler pressure, in  $^{\circ}C$ .

It was considered that for steam generation the heat transfer by radiation is prevalent. In that sense, the efficiency of the heat transfer should not be affected by the boiler-load reduction due to vapor deviation to solar receiver. However, for the superheater it is assumed the heat transfer by convection is dominant. Thus, since Nusselt number is related to Reynolds by a power of 0.8,  $U$  was estimated to vary with  $\dot{m}_{boiler}$  to same power.

$$\dot{Q}_{SH} = (U_{max} \cdot A) \left( \frac{\dot{m}_{boiler}}{\dot{m}_s} \right)^{0.8} (T_{out,boiler} - T_s) \quad (5)$$

Where,  $U_{max}$  is the maximum global coefficient of heat transfer, in W/m<sup>2</sup>K;  $\dot{m}_s$  is the mass flow of steam required for plant operation, in kg/s.

The energy balance of the solar plant and the total energy balance is given by:

$$\dot{Q}_{solar} = \dot{m}_{solar} (h_{out,solar} - h_{in}) \quad (6)$$

$$\dot{Q}_T = \dot{Q}_{solar} + \dot{Q}_{boiler} = \dot{m}_s (h_{out} - h_{in}) \quad (7)$$

Where,  $\dot{Q}_{solar}$  is the heat supplied by the solar plant, in kW;  $\dot{m}_{solar}$  is the mass flow of water passing through the solar plant, in kg/s;  $h_{out,solar}$  is the enthalpy at the output of the solar field, in KJ/Kg;  $\dot{Q}_T$  is the total heat supplied to power plant, in kW;  $h_{out}$  is the enthalpy of enthalpy at system output, in kJ/kg.

Considering these balances, as well as the variation of the enthalpy of the boiler as a function of the temperature of the boiler, a system of 5 non-linear equations was set up which provided the specific quantities of mass flow of the solar field, and of the boiler, as well as the enthalpies of each of them and the temperature at the boiler outlet. The system was solved using the Newton Raphson method.

With the mass flow values of the boiler and the solar field, it is possible to calculate the maximum amount of bagasse that is used from the boiler efficiency ( $\eta_{boiler}$ ) and the maximum total amount of heat ( $\dot{Q}_T$ ) that the system can receive:

$$\eta_{boiler} = \frac{\dot{Q}_{boiler}}{\dot{m}_{bag} PCI_{bag}} \quad (8)$$

$$\dot{Q}_{fuel_{max}} = \frac{\dot{Q}_T}{\eta_{boiler}} \quad (9)$$

Where,  $\dot{m}_{bag}$  is the is the mass flow rate of bagasse consumed in the boiler, in kg/s;  $PCI_{bag}$  is lower calorific value of wet bagasse, in kJ/kg;  $\dot{Q}_{fuel_{max}}$  is the maximum heat quantity of biomass at full load, in kW.

From Eq. (8) and Eq. (9), the maximum mass flow of bagasse ( $\dot{m}_{bag,max}$ ) is given by:

$$\dot{m}_{bag,max} = \frac{\dot{Q}_{fuel_{max}}}{PCI_{bag}} \quad (10)$$

Thus, it is possible to obtain the amount of bagasse used, and consequently the amount of bagasse that was stored, from the steam biomass ratio ( $R_{s/b}$ ):

$$R_{s/b} = \frac{\dot{m}_s}{\dot{m}_{bag,max}} \quad (11)$$

$$\dot{m}_{bagasse} = \frac{\dot{m}_{boiler}}{R_{s/b}} \quad (12)$$

$$\frac{dm_{bag,stk}}{dt} = \dot{m}_{bag,max} - \dot{m}_{bagasse} \quad (13)$$

Where,  $\frac{dm_{bag,stk}}{dt}$  is the total quantity of bagasse stocked in kg;  $\dot{m}_{bagasse}$  is the is the mass flow of bagasse entering the boiler, in kg/s.

### 3. RESULTS AND DISCUSSION

The SAM uses data from different years and generates the TMY for the analyzed station every hour. With the data of DNI of the TMY was generated the solar year for Brasília (Fig. 4), and from it, is possible to see that the best months

for generation are between June and September. These months are part of the dry season. For the Brazilian electricity sector, the year is divided between a wet and dry period, related to hydrological conditions for power generation. The wet period is from December of one year to April of the next year, and the dry period occurs between the months of May and November. In the 2016/2017 harvest, 96% of the cane produced was processed in the dry season. With this behavior as base, the implantation of the solar field would cause that less sugar cane to be processed in that period, being able to be used for period of off-season (UNICA, 2018).

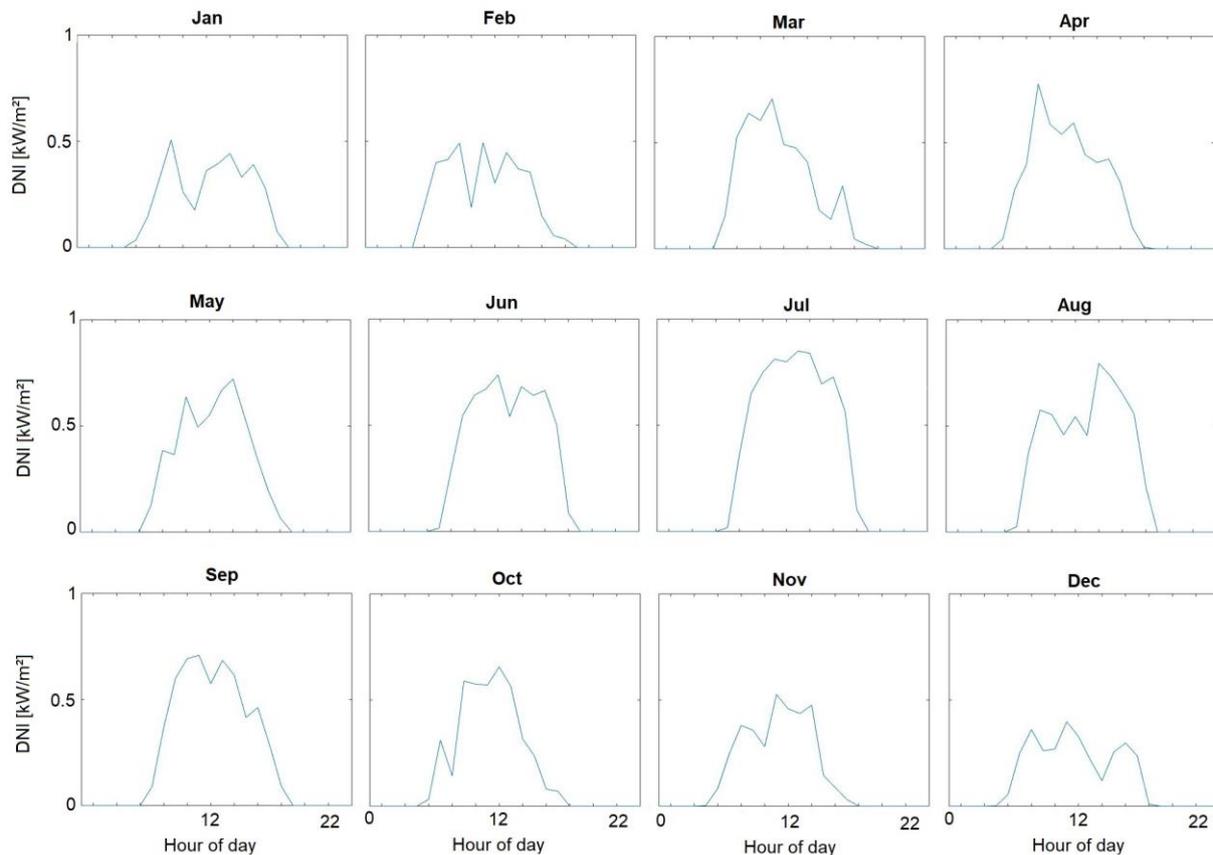


Figure 4. Typical Meteorological Year

The simulation was done for a central tower concentrated solar power plant of 45MW, solar multiple of 1.5 with no thermal storage. The solar field obtained by SAM optimization method resulted in a total reflective area of 310400 m<sup>2</sup>. It was made so that the solar and biomass systems always provided the amount of steam needed to operate the plant (42.5 kg<sup>-1</sup>), varying only the amount of biomass that would be used as solar energy was captured. At times without solar radiation, the energy supplied would be only from the burning of the bagasse. From these values, it was possible to find the mass of steam generated in the boiler and in the solar field, for each hour, thus estimating the quantity of bagasse saved. Figure 5 shows the average monthly bagasse economy and the amount of bagasse stored during the sugarcane harvest period from April to October.

The largest bagasse economy occurs in the months of June to September, since it is the months of higher direct normal solar radiation and, consequently, of greater capacity for generating solar energy, reducing the demand for energy from bagasse burning.

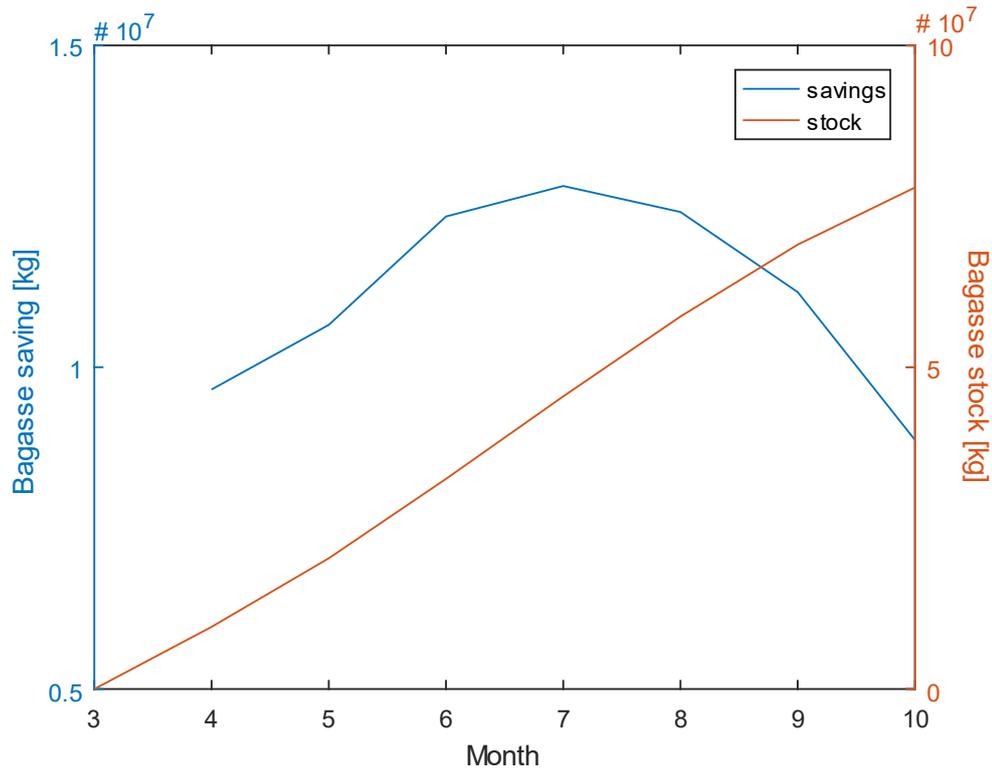


Figure 5. Average monthly savings and bagasse stock in the harvest

Table 1 shows the amounts of bagasse currently used by the plant, and the savings that would be made with the implantation of the solar field. With the implantation of the solar field, it would be possible to stock during the harvest period about 77 thousand tons of bagasse to be used during off-season from November to March. This amount could supply an average monthly consumption of up to  $27 \text{ Th}^{-1}$  of bagasse, which is the bagasse mass flow that the plant would require in the off-season after the implementation of solar field. In addition, with the solar field, the plant uses less bagasse, and manages to meet more than the required demand of bagasse, which is currently not supplied.

Table 1. Bagasse consumption, economy and stock with and without solar field

Parameter	Unity	Value
Total bagasse production	T	714286
Bagasse consumption without the solar field (crop)	T/h	173
Bagasse consumption with the solar field (crop)	T/h	126,18
Bagasse consumption without the solar field (off season)	T/h	41.49
Bagasse consumption with the solar field (off season)	T/h	27.74
Bagasse economy	%	27.06
Current stock at the end of a harvest	T	14286
Stock of bagasse at the end of harvest with solar field	T	77866
Steam/bagasse ratio	T/T	1.88

#### 4. CONCLUSIONS

In this work, was made an evaluation of the amount of sugarcane bagasse that could be saved and stored in an energy cogeneration plant (ethanol + electric energy) from a CSP plant. For this, a solar field was modeled in the SAM using the central tower technology with generation of 45 MW in parallel with the boiler, which operates in Rankine cycle. The load of the boiler varied according to the solar incidence, but operated with at least 30%, and the system composed of the solar plant and the biomass burning always provided the fixed mass flow rate of steam that the turbines demand.

The SAM simulation provided the typical meteorological year, which showed that the best periods for energy generation are in the same period as the sugarcane harvest, reducing the need for energy generation by burning biomass and making it possible to store more bagasse for be used in the off season.

From the simulation performed it was possible to estimate that the plant could save 27% of bagasse during the harvest. This economy would make it possible to store about 77 thousand tons of bagasse, which is approximately 5.5 times bigger than the current security stock. Another positive point is that the implementation of the solar field would solve a problem that the plant has, which is not having the amount of bagasse needed for maximum generation of electric energy.

This study was promising, as it obtained results that would solve current problems of the plant studied and still favor it in the electric energy market, which is already inserted, increasing its generation in the off-season, in which its operation is reduced. In addition, would make use of renewable energies, solving two problems associated with the sources used, which is the intermittency and seasonality.

## 5. ACKNOWLEDGEMENTS

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