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COMPARISON OF A HYBRID CSP-BIOMASS POWER PLANT PERFORMANCE INTO TWO DIFFERENT CLIMATE CONDITIONS

Pedro Henrique Dias de Véras Sousa
Mário Benjamim Baptista de Siqueira
Universidade de Brasília, Faculdade de Tecnologia, Laboratório de Energia e Ambiente, 70910-900 Brasília, DF, Brazil
phdveras@gmail.com, mariosiqueira@unb.br

Abstract. *In the present work, a hybrid power plant using Concentrated Solar Power (CSP) and biomass (bagasse) technologies is investigated in terms of annual energy production. Real data from a Brazilian sugar-cane power plant located in the state of São Paulo is used. The plant crushed about 1.5 million tons of sugar-cane in 2015, producing ethanol and approximately 175 GWh of electricity with a 30 MW power block. CSP performance using central tower technology was evaluated using the free software System Advisor Model (SAM), developed by the U. S. National Renewable Energy Laboratory (NREL). Three different CSP power configurations and two cities, one in the Midwest and another in the Northeast of Brazil, were considered. Results have shown a considerable increase in annual energy production compared to biomass-only case, indicating potential benefits in using hybridization.*

Keywords: *hybridization, CSP, sugar-cane biomass, solar energy, System Advisor Model.)*

1. INTRODUCTION

Most of Brazilian electric energy comes from hydraulic sources. For instance, according to the *Empresa Brasileira de Pesquisa Energética*, (EPE, 2015), these sources contribute with more than 60% of the internal generation of electric energy in the country. However, the water crisis in recent years, which resulted in an increase in energy tariffs, showed the fragility of a system greatly based on this energy source.

In this regard, biomass, mostly from sugar-cane, is another important energy source in Brazil, accounting for 7.6% of Brazilian total energy generated in 2014 (EPE, 2015). In many of the sugar-cane plants where sugar and/or ethanol is produced, they use the bagasse, a leftover product from the crushing process, as fuel to be burned into boilers, producing steam at high temperature and pressure, which is further used in the generation of electric energy and for the plant's processes. Since the plant's needs for electricity is lower than its generation, it is common for them to sell the excess for local energy dealers. Anyway, the problem is that many of these plants only produce energy during harvest season, when there is an inflow of sugar-cane to crush, and therefore bagasse to burn. Moreover, they are affected by their surroundings, which limit biomass availability and specially transport cost, and by fluctuations in price (Coelho *et al.*, 2015).

Considering Brazil's solar potential (Pereira *et al.*, 2006) one can see that many of these sugar-cane power plants are located in regions where Direct Normal Irradiation (DNI) resources are high, in a corridor that extends from the states of Mato Grosso do Sul until Pernambuco and where Concentrated Solar Power (CSP) is highly suitable (Rodrigues and Siqueira, 2015). A downside for this technology though is the cost of the thermal storage system, essential when the energy is supposed to be continuously delivered. Therefore, a CSP and biomass hybridization, where the solar field provides steam to the sugar-cane plant when solar radiation is high enough, can be beneficial for both technologies, as it improve the energy capacity of biomass power plants, allowing them to stock bagasse during favorable solar conditions, while reducing the need for CSP thermal storage (Servert *et al.*, 2011).

In this work, potential benefits of CSP-biomass hybridization are studied using data acquired from a real sugar-cane power plant in the year 2015 and simulations performed in the free software System Advisor Model (SAM). In order to investigate the effect of local climate conditions in the results, two different locations are analyzed one at the Midwest and another in the Northeast of Brazil.

2. METHOLOGY

2.1 Sugar-cane power plant

The biomass power plant chosen for this work is located in the northwest of the state of São Paulo and only produces ethanol. Its harvest season in the year 2015 occurred from the end of March until late December, when close to 1.5 million tons of sugar-cane were crushed and 200 million litters of ethanol produced.

Its power cycle has a single boiler capable of generate 200 tons of steam per hour, at 67 bar and 490° C. Te steam is expanded in a back-pressure turbine coupled to a 30 MW electrical generator to produce the electricity that serves the internal demand of the plant, mainly due to the fact its millings are powered by electrical motors. The remaining energy is negotiated with the local energy dealer. Moreover, since it is a back-pressure turbine, the steam leaving it is still used in other processes in the plant. Figure 1 below shows schematically the sugar-cane power plant studied in this work.

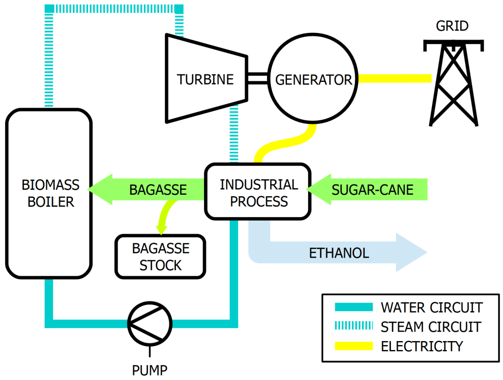

Figure 1. Scheme of the sugar-cane power plant analyzed.

In the case of the hybrid power plant, the steam generated by the CSP is not supposed to provide the total demand of the sugar-cane power plant, rather, it should add to the steam leaving the biomass boiler and therefore reducing its necessity for burning bagasse and increasing biomass savings. During night period and/or when solar conditions are not favorable for generating steam in the CSP plant, the biomass boiler should operate alone, supplying the sugar-cane plant's necessities. This functioning is shown in Fig. 2 below.

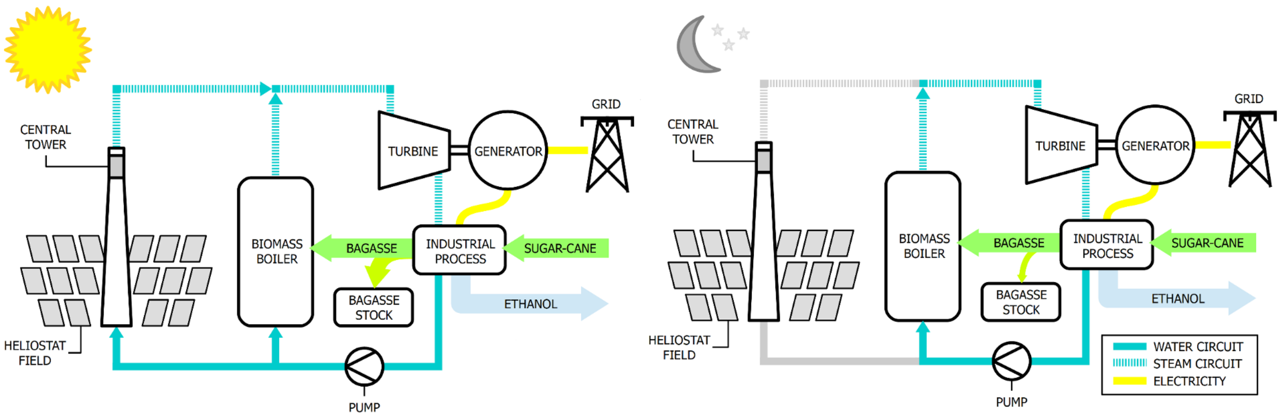

Figure 2. Scheme of the hybrid CSP-biomass solution proposed.

2.2 System Advisor Model

SAM, the software used in the analysis and sizing of the CSP system and developed by the *U. S. Department of Energy* and the *National Renewable Energy Laboratory* (NREL) is a complete simulation tool developed to aid on the decision making of people involved with renewable energy, providing technical and financial data from the many inputs inserted by the user (NREL, 2017).

The user can choose between several options of renewable energy systems, such as solar, wind, biomass and geothermal. In the case of solar energy, SAM has the four major CSP technologies: power tower, parabolic through, linear Fresnel and dish Stirling. Since the biomass power needs a significant amount of steam at high temperature and pressure for its operation, the CSP model with central power tower was the chosen.

SAM uses several sources to create an very extensive database with weather conditions for various cities around the globe. In this study, both cities had its information already available in SAM, which gathered it from SWERA (*Solar and Wind Energy Resource Assessment*). This data, along with the other user's inputs, is used to generate an hourly performance and financial simulation of the power plant.

Another SAM's feature is its ability to optimize the CSP solar field. Based on user's parameters and local weather conditions, the software estimates the best combination between heliostats distribution, tower height and receiver characteristics for minimum direct cost. Since many configurations were compared in this work, before each simulation, the heliostat field was optimized.

2.3 Analysis method

The analysis start with the monthly data of sugar-cane power plant. While the biomass power plant can vary its power production during harvest season, the hybrid power plant is designed to keep energy generation as high as possible throughout the year. Thus, from the total amount of energy generated by the power plant and the total of days during harvest season, a simple daily average energy generation was calculated. Then, the monthly energy generated by the hybrid solution, in MWh, was evaluated by Eq (1) below:

$$EG_{hyb,month} = N_{d,month} \times \left(\frac{EG_{biom,harvest}}{N_{d,harvest}} \right) \tag{1}$$

where $N_{d,month}$ is the number of days in a month, $EG_{biom,harvest}$ is the total amount of energy generated by the biomass power plant, in MWh, during harvest season and $N_{d,harvest}$ is the number of days of harvest.

Also, from the monthly amount of sugar-cane processed in the millings, it was possible to estimate the bagasse inflow into the power plant. Although not necessarily all of this bagasse is burned in the biomass boiler right away, thus going directly to the stock, the monthly energy generation data and this biomass balance can be used to evaluate the average energetic efficiency of the bagasse in terms of MWh per ton of biomass. To do so, Equation (2) was used:

$$EE_{bagasse} = \frac{EG_{biom,harvest}}{BAG_{steam,harvest}} \tag{2}$$

where $BAG_{steam,harvest}$ is the amount of bagasse burned in the biomass boiler to generate steam during harvest.

In the case of the CSP plant, the cities of Campo Grande/MS and Recife/PE were considered, since one of the goals of this work was to compare the hybridization performance in different climate conditions and since their solar resources data were already available in SAM. The heliostat field optimization was made using an design point DNI of 850 W/m^2 and considering a unitary solar multiple. In all cases, the heliostat dimensions were fixed, being 7.5 m wide and 12 m high. All other characteristics were set to default values.

Furthermore, since SAM estimates the annual energy based on the gross output of a design turbine, three different configurations were simulated: 30 MWe, 35 MWe and 40 MWe. Despite many variables could be controlled in SAM, the other things changed were the pressure and temperature of the steam in the power cycle to match the values of the biomass power plant, i.e., 67 bar and 490° C.

However, after simulate a case, SAM gives the monthly electric output in MWh, but the goal of hybridization is for the CSP power plant to supply part of the steam required to run the biomass power plant and, this way, save some bagasse which can be used latter. Therefore, it was necessary to somehow convert this electric output in to a *saved bagasse* equivalent. To do so, it was assumed that thermodynamic efficiency of the power cycle of the CSP plant is 37% and that the lower heating value of the bagasse is 7,600 kJ/kg (Rodrigues and Siqueira, 2015). Thus, the amount of bagasse saved every month by the hybridization, in tons, is equal to:

$$BAG_{saved} = \frac{EG_{CSP}}{0.37 \times 7,600} \times 3,600 \tag{3}$$

where EG_{CSP} is the monthly electric energy output in MWh of the CSP given by SAM. The balance in bagasse in stock varies each month depending on the bagasse saved, the sugar-cane inflow and the energy generated by the power plant, that is:

$$BAG_{stock,i} = BAG_{stock,i-1} + BAG_{saved} + BAG_{inflow} - BAG_{steam} \tag{4}$$

where $BAG_{stock,i-1}$ is the bagasse stock in the previous month and BAG_{inflow} is the bagasse coming from the sugar-cane crushing. In the end of harvest season, this saved bagasse can still be burned in the biomass boiler, despite there is no sugar-cane inflow. Moreover, the CSP plant should still able to generate energy during this idle period, increasing energy generation.

3. RESULTS AND DISCUSSION

Starting with the energy generation, Figure 3 below shows both monthly energy generated by the biomass power plant in 2015's harvest and the expected energy generation of the hybrid solution.

The average energy generation was 642 MWh/day, but it was calculated considering only the ten months of harvesting of the biomass power plant. Thus, although the maximum energy generated by the CSP-biomass power plant is kept

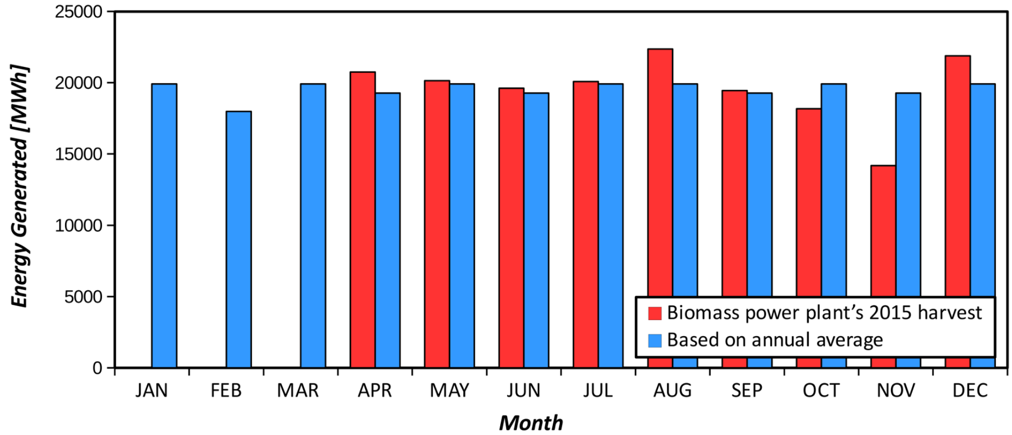

Figure 3. Monthly energy generated by the biomass power plant and maximum energy generation by the hybrid solution.

almost constant all over the year in Fig. 3, it should be noticed that during idle period this value is expected to reduce, since it will depend on other factors such as bagasse availability in stock and solar conditions.

The other information obtained from the biomass power plant was its sugar-cane inflow and the amount of bagasse burned in the boiler. Figure 4 below shows the amount of sugar-cane crushed every month during the season, how much of that became bagasse and the portion that was burned for generating steam.

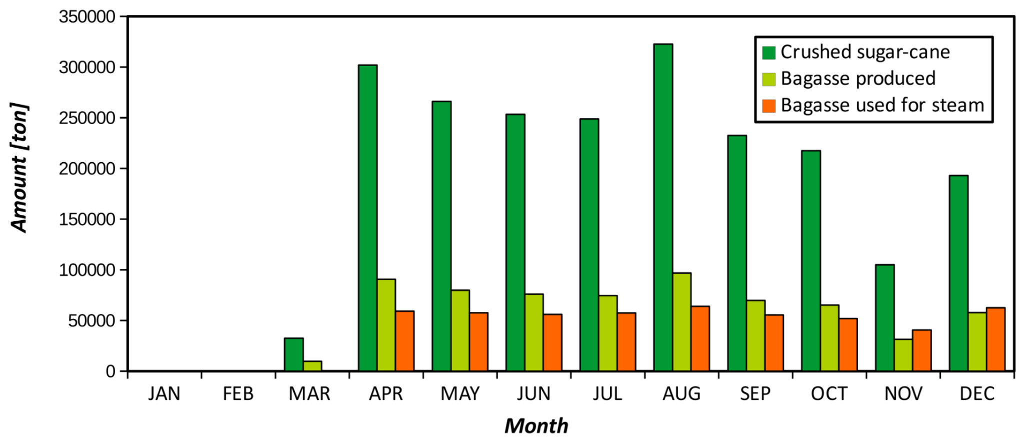

Figure 4. Sugar-cane and bagasse data from biomass power plant's 2015 harvest season.

Harvest period was considered from April to December despite the small quantity of sugar-cane crushed in March. From Fig. 4, it is also possible to see that there is a sudden drop in the crushing in November, possibly due to a rainy period that year, which difficult the access of the trucks into the plantations and into the plant itself. Furthermore, it should be noticed that, for the particular case of the biomass power plant studied, the amount of bagasse produced is higher than the amount burned in the boiler. Thus, the amount of sugar-cane processed is higher than plant's needs to keep energy generation close to 20 MWh/month and bagasse is sent to stock due to non use

However, since both graphs in Figures 3 and 4 are closely related, it is possible to see that the stock of bagasse was used along the year to keep the energy production more stable. Even with the peak in August and drop and November in sugar-cane crushing, the biomass power plant kept its generation close to 20 MWh/month during the whole harvest season. Then, from the values on these graphs and considering only the period between April and December, the evaluated energetic efficiency of bagasse was 0.35 MWh per ton of bagasse.

For the design of the CSP power plant, SAM simulated typical solar conditions in the two cities considered and Figure 5 below shows the averaged hourly results of DNI. From the results it is possible to see that Recife/PE presents a more constant radiation throughout the year, with peaks close to the end of the year. On the other hand, Campo Grande/MS has a greater variation of DNI, but its peaks are higher than Recife's. Since harvest season in Northeast is different from Midwest, but they both occur in the sunniest period, a CSP power plant in Campo Grande/MS should generate more energy due to these higher peaks.

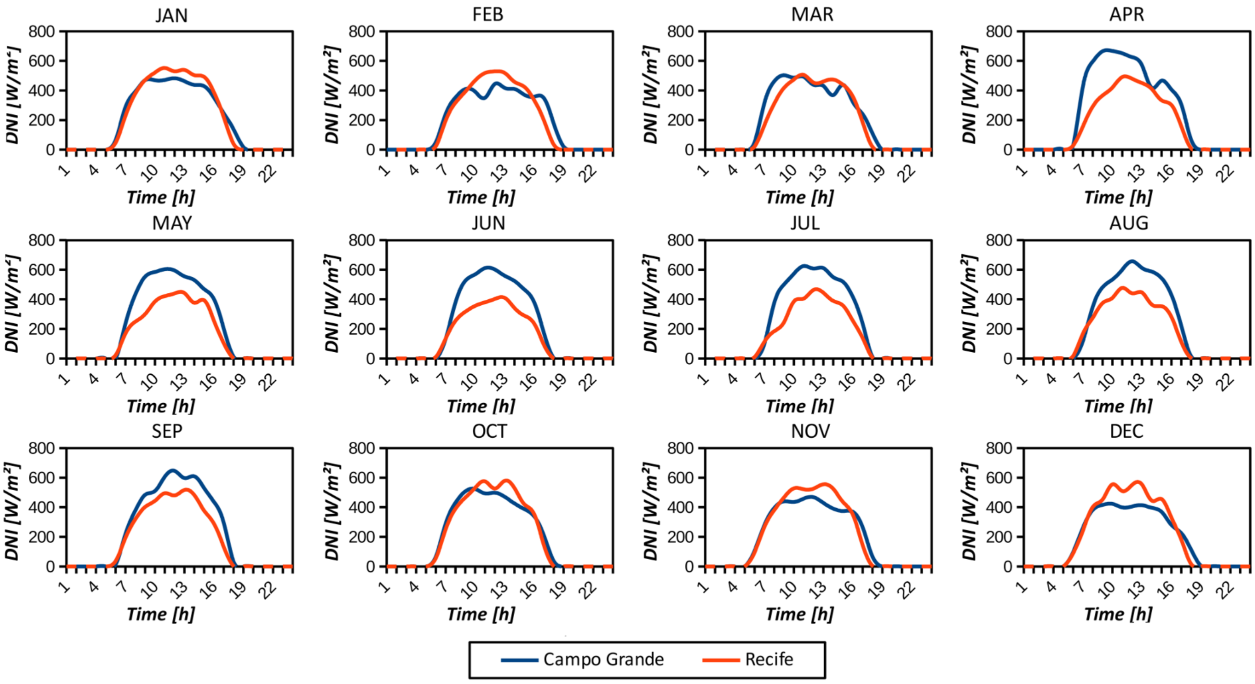

Figure 5. Solar data for Campo Grande/MS and Recife/PE from SAM.

Based on these values, SAM evaluated the total electric energy produced, in MWh, by the CSP plant every month. Then, assuming a 37% power cycle efficiency of the CSP, the amount of heat generated by the solar plant was evaluated and latter used to calculate the bagasse savings. Figures 6 and 7 show the energy and heat generation in both locations calculated by SAM.

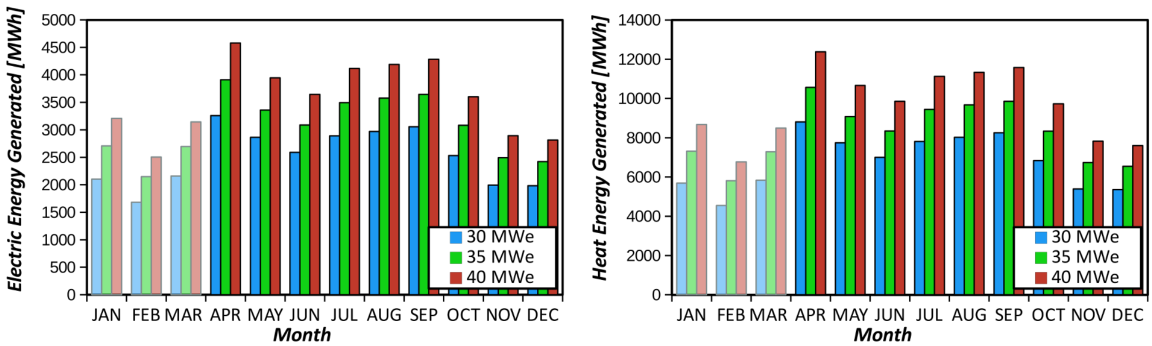

Figure 6. Electric and heat energy generated by the CSP in Campo Grande/MS.

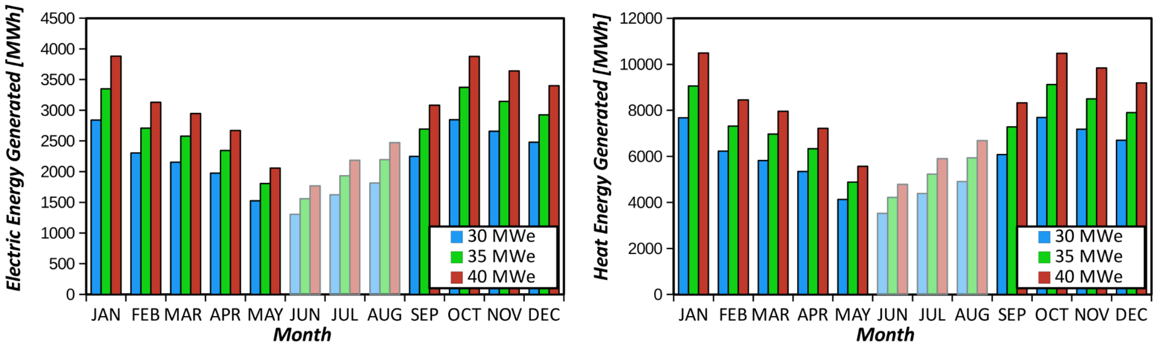

Figure 7. Electric and heat energy generated by the CSP in Recife/PE.

It should be noticed from Fig. 6 and 7 that during part of the year the heat generated by the CSP is not converted in *bagasse savings*. As seen in the actual data from the biomass power plant, harvest is about ten months long. However, this period changes depending on the region. For instance, in Campo Grande/MS the harvest period was considered as being the same of the studied biomass plant. In Recife/PE, however, this period was shifted so it goes from September to May. Thus, to evaluate the savings in Recife/PE, the results in Fig. 3 and 4 are also shifted.

Then, knowing the lower heating value of the sugar-cane bagasse, the monthly saving of biomass could be estimated from the heat energy generated shown in Fig. 6 and 7. These results are shown in Fig. 8.

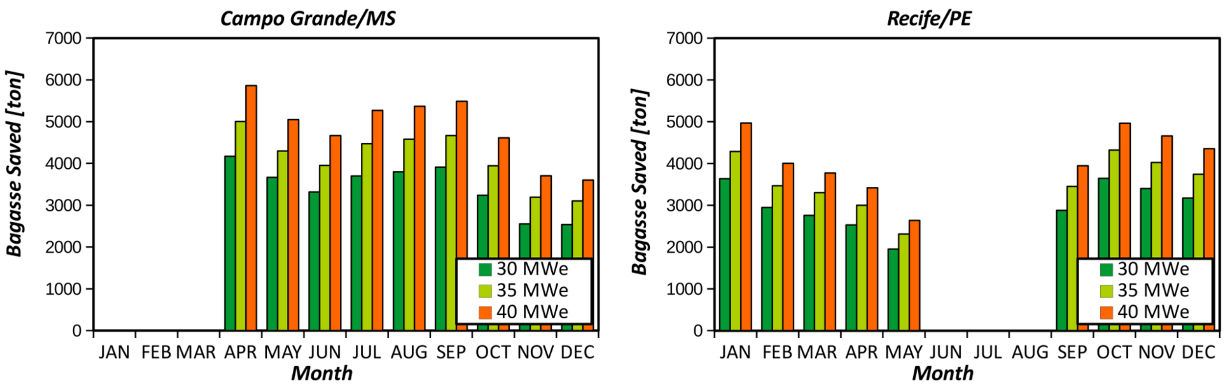

Figure 8. Equivalent monthly bagasse saved by the CSP plant in both locations.

As expected, savings of bagasse were greater in the moths with higher DNI. However, since the amount of sugar-cane crushed varies along the year and energy generation was considered as being constant, it means that the stock of bagasse might even reduce during some period, although the CSP plant *always* acts in the sense of saving biomass.

By keeping track of the bagasse balance throughout the year in the hybrid scenario, it was possible to determine the amount of stock at the end of harvest season. Then, using the bagasse efficiency analyzed previously, the energy increment achieved by using a hybrid CSP-biomass plant was evaluated. Results are shown in Tab. 1.

Table 1. Energy increment by hybridization.

CASE		ANNUAL ENERGY GENERATED (GWh)	ENERGY GAIN (GWh)	% INCREMENT
Campo Grande/MS	30 MWe	195.0	18.4	10.4
	35 MWe	199.3	22.7	12.9
	40 MWe	203.2	26.6	15.1
Recife/PE	30 MWe	192.1	15.5	8.8
	35 MWe	195.1	18.4	10.5
	40 MWe	197.7	21.1	11.9

In all scenarios analyzed, introducing a CSP plant ended up increasing the annual energy generation capacity of the power plant. Furthermore, as expected, since Campo Grande/MS has a higher DNI along the year compared to Recife/PE, its annual energy gain was bigger, with the 30 MWe increasing the energy generation in as much as the 35 MWe in Recife/PE. Nonetheless, in both cities, increasing the CSP plant power capacity seemed to have a linear effect on the increment, but again, Campo Grande/MS has a higher slope.

4. CONCLUSIONS

The main purpose of this work was to evaluate the performance of a hybrid CSP-biomass power plant in two different locations: Campo Grande/MS and Recife/PE. During favorable conditions, the CSP installation directly delivered steam for the sugar-cane power plant, allowing it to save and stock its fuel. Real data from the 2015 harvest season allowed us to calculate an energetic efficiency of 0.35 MWh/ton for the bagasse. Moreover, SAM provided the energy data of the CSP plant, so the monthly amount of steam generated by the solar plant could be addressed and the savings of bagasse estimated.

The analysis of 30 MWe, 35 MWe and 40 MWe configurations have shown promising results. In the most favorable solar conditions, which correspond to Campo Grande/MS, the energy increment was up to 15%. However, Recife/PE also showed a significant increase in energy production.

Nonetheless, the results have shown that larger solar fields increase the energy gain, meaning that other scenarios should still be investigated in order to understand what would be the optimum CSP power capacity for the hybridization. However, this also means that more detailed thermodynamic analysis and financial simulations should be conducted alongside testing these other scenarios so a better perspective of the real gains of hybridization can be addressed.

5. ACKNOWLEDGEMENTS

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