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# A CASE STUDY OF AN HYBRID SOLAR - SUGAR-CANE BIOMASS POWER PLANT

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***Abstract.*** *In this work, a case study of a hybrid solar-sugar cane biomass power plant was investigated. The motivation to do so is that in co-generation systems based on the sugar-cane bagasse (biomass left-over after cane juice is extracted), a system adopted in several ethanol-sugar mills, the power block is idle in between harvest seasons (5 to 6 months). A study-case of a real sugar-cane mill located in the state of Goiás was performed. The mill has a 40MW power block installed (two steam turbines) as part of its co-generation system, which generated a mean value of approximately 18.700MWh per month during last harvest season (May to November). Simulation of solar field performance was done using the freely available System Advisor Model (SAM) developed by USA National Renewable Energy Laboratory (NREL). The CSP technology of choice was central tower. Results show that the addition of the CSP system could increase annual energy generation up to 26% and made possible to sustain the power generation at full capacity for 4 months beyond current operation.*

***Keywords:*** *Renewable energy, solar energy, sugar-cane biomass, cogeneration*

## 1. INTRODUCTION

The recent hydrological crisis in Brazil, due to a multi-year drought, revealed severe vulnerabilities of the country´s energy sector. Of Brazil´s power generation internal supply, about 70% is concentrated in hydroelectricity (EPE, 2014), so it relies heavily on the state of the reservoirs. The last two years of lower-than-normal precipitation on southeast and center-west regions of the country, which concentrate a large number of reservoirs, put regulated energy-consumption restriction on the discussion table, which would worsen the present economic downturn. The current crisis may not be a isolated event, given that global-climate-change modeled scenarios suggest, although with large variability between models, a decreasing trend of precipitation for the region (Vera *et al*., 2006).

On the other hand, biomass-derived electric energy, mainly from sugar-cane sugar/ethanol production cogeneration plants, was responsible for 7.6% domestic electricity supply in 2013(EPE 2014). These plants burn sugar-cane bagasse, left over from sugar-cane crushing, in boilers to produce high temperature and pressure steam for power generation and process vapor. However, the power block remains idle during inter-harvest season (usually 5 to 6 months) when there is no sugar-cane biomass to burn.

Some of these sugar/ethanol production plants are located in regions where solar resources are high. Solar-resource mapping shows that there is a corridor of high direct normal irradiance (DNI) that covers the area from the southwest of the state of Pernambuco down to the northeast of Goiás (Martins, *et al*., 2012). This region is identified as highly favorable for concentrated solar power (CSP) plants. However, for a continuous dispatchable power, CSP requires a heat storage system to be used at night or low-DNI periods. The cost of such system may be prohibitive and compromise the economic viability of the CSP project.

One alternative solution would be integrate a CSP direct steam generation system (with no storage) to a sugar-cane biomass cogeneration plant in a hybrid arrangement (Servert *et al.*, 2011). Since the biomass is produced on site, the CSP-derived vapor could be used when DNI is sufficiently available in addition to biomass, enhancing power dispatchability and allowing storing bagasse that would make the power-block annual power generation period longer. In this work, this solution was investigated for an ethanol production cogeneration plant. The case study used data for year 2014, period where sugar-cane biomass production and power generation of a real plant were made available to us. The study made use of a simulation platform developed National Renewable Energy Laboratory (NREL, USA). A brief description of the plant and the simulation tool is provided next.

## 2. MATERIALS AND METHODS

In this case study, the addition of a Concentrated Solar Power (CSP) system to a typical sugar/ethanol production plant with cogeneration was investigated. It was considered that the plant is located in Brasília, Distrito Federal, Brazil, approximately 180km from actual plant location, given that the solar-radiation components data are freely available through "Sistema de Organização Nacional de Dados Ambientais (SONDA)" (INPE, 2015) which maintains a solarimetric station in Brasília. Additionally, Brasília is in the border of high-DNI region in the central region of Brazil.

The CSP system is considered as a source of superheated water vapor to feed the steam turbines and industrial processes in parallel with currently installed biomass boilers. The CSP configuration chosen for this study was central-tower receiver with direct steam generation, given that current installation requires steam in excess of 400$^{o}$C and biomass is available most of the time to cover for nighttime and low-DNI periods, avoiding the use of high-cost heat-storage measures. Operationally, the supplement vapor from the CSP system would allow sugar-cane bagasse to be stored and used as needed to enhance power generation.

The study made use of the System Advisor Model (Blair *et al.*, 2014) platform, a software developed by the NREL designed for technical-economical studies of renewable-resource use for electric power plant projects. The ethanol production plant studied is a typical cogeneration plant where data from the 2014 harvest year were made available for this investigation.

### 2.1 The Ethanol Production Plant

The plant production capacity is 800 m$^3$ of ethanol per day from crushing a maximum of 10,000 tons of sugar cane. From the total amount sugar-cane processed, an average of 26 to 27% is left over as sugar-cane bagasse. The biomass is burned in two boilers able to provide steam at 490 $^{o}$C in temperature and 65 bar in pressure. Steam is expanded in two steam turbines, one working on counter-pressure mode e other at vacuum, coupled with electric generator with nominal capacity of 28 MW and 20 MW, respectively. Counter-pressure steam turbine provides vapor for the industrial processes required for ethanol production. Crushing mills are powered by electric motors. The power generation plant works during the harvest season, which extend typically between 6 to 7 months of the year. Figure 1 shows a schematic diagram of the existing plant and proposed arrangement to use solar energy to enhance annual power generation, with the bagasse stored or used as solar radiation is available or not.

### 2.2 SAM Simulation Tool

SAM is a simulation tool designed to facilitate researchers and engineers in technical-economical evaluation of potential use of renewable energy for electric generation purpose. It allows users to choose a certain energy-generation arrangement from several renewable resource (solar, wind, biomass or geothermal). For solar, it contemplates the four main solar-concentration technologies. After the choice of an appropriate technology, CSP with direct steam generation in this case, it populates the input variables with reasonable default values. Users can than edit the values for the specifics of the problem in question. SAM is able to get meteorological and solarimetric data directly from several sources, if it is available online. That is the case for the data set from SONDA program. SAM's calculation engine, performs a time-step-by-time-step simulation of a power system's performance, and calculates project cash flow and financial metrics annually.

An SAM tool relevant for the present analysis is the solar-field optimization. Based on users-defined parameters, the optimization scheme (Wagner, 2008) estimates the best heliostat distribution, tower height and receiver characteristic, for minimum direct cost. This was important for the study here because performance is sensitive to solar-field configuration, which is function of power rating and heliostat dimensions.

### 2.3 Analysis Methodology

Since SAM calculates electric energy output, the heat input by the solar system was estimated based on a efficiency of the power block. Different configurations were modeled by varying nominal CSP power level for each run. Performance was evaluated considering different power levels and heliostat dimensions, using SAM solar field optimization wizard. This heat input was considered as sugar-cane bagasse saved based on its heating value. The idea is to use the additional heat input from the CSP system to work with bagasse production to extend power production beyond harvest season, taking advantage of the idle time in between harvest seasons.

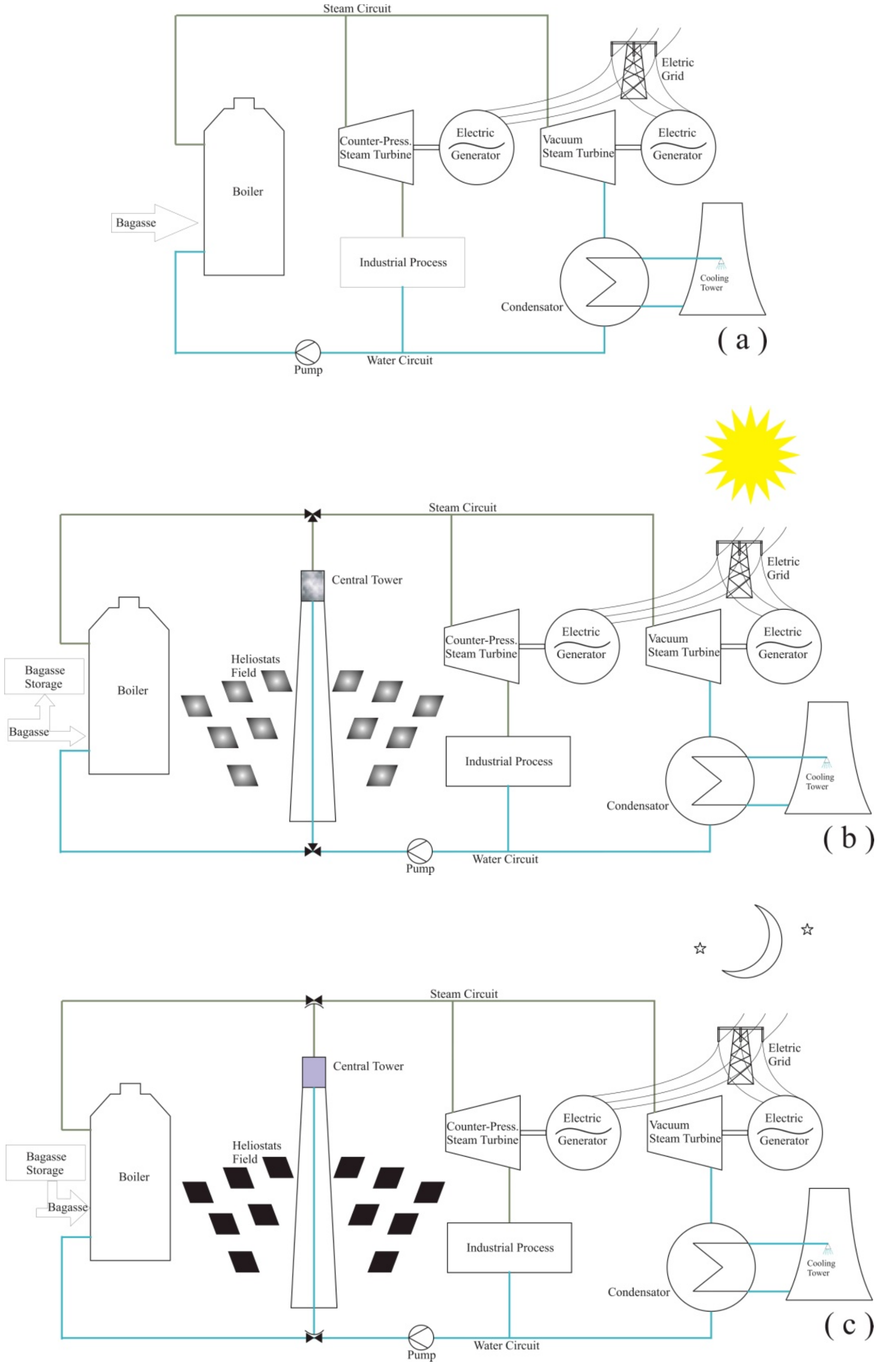


Figure 1: Schematic diagram of the cogeneration plant. Panel (a) shows the original current situation, panel (b) is the proposed arrangement with central tower solar field with solar radiation available and panel (c) same as (b) but for periods when solar radiation is unavailable.

## 3. RESULTS AND DISCUSSION

SAM gets the multi-year measured meteorological data and generate typical-year hourly time series with the proper statistics. The direct solar irradiation (DNI) generated by SAM from the solarimetric station nearby Brasília is shown in figure 2,which shows an average day for each month. Brasília´s climate is characterized by two very distinct seasons, a wet season from November to March and a dry season from May to September, with months of April and October being transitions between them. Given the high cloudiness during the wet season, DNI tends to be lower. Consequently, best DNI periods occur from May to September.

The procedure described in the previous section was performed for nominal power levels of 40 MW, 50 MW, 60 MW, 70 MW and 80 MW with a solar multiple of 1. The choice of solar multiple comes from the fact that there is no heat storage and biomass can provide heat when solar radiation does not meet energy demand. Since energy output are sensitive to the size of the heliostats, a trial and error scheme was performed to get a optimal heliostat dimensions on top of the optimization of heliostat field implemented in SAM, which finds the optimal configuration for the solar field for a minimum levelized cost of energy given heliostat dimensions. Square heliostats were considered with sides ranging from 2.5 m to 10 m in increments of 2.5 m. The variable considered to find optimal heliostat were energy output per initial direct installation costs, which include heliostat field, tower and land acquisition. Cost parameters for heliostat and tower were kept unchanged from default values in SAM and land price were set to U$2000 per acre, price got from a sample of land for sale in the vicinity of Brasília. Figure 3 depicts annual energy per direct cost dollar amount as a function of the heliostat size for the five power levels. It shows an increase from 2.5 m heliostat size but it tends to level off as heliostat size increase.

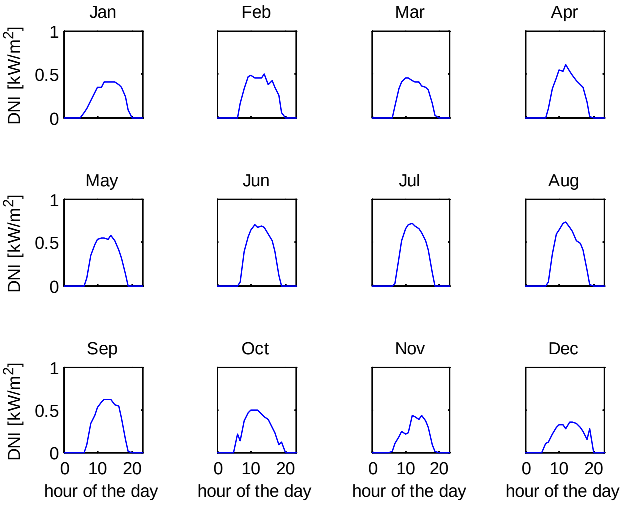


Figure 2. typical-day DNI for each month of the year

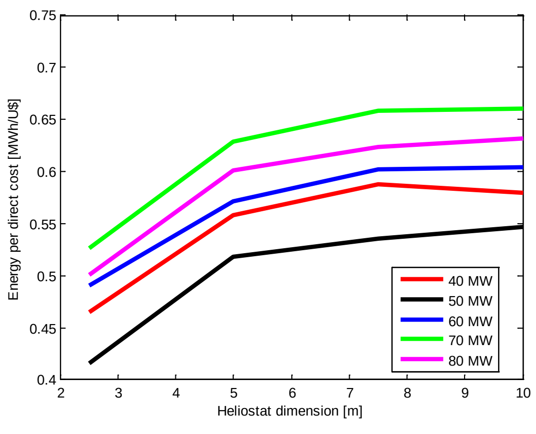


Figure 3. Energy generated per direct cost ratio for different heliostat dimension and each nominal power level

It is important to note that the indicator does not necessarily increase with the power level, as it is clear from the fact that 40 MW and 70 MW provide higher values then 50 MW and 80 MW, respectively. This is due to an increase in tower height given by SAM optimization when moving from those power levels. Interestingly, the tower height for the power levels of 50 and 60 MW were increased in the optimization when the heliostat size was changed from 7.5 m to 10 m (result not shown). In fact, the highest tower from all runs (192 m) were for power level 50 MW, which made the smaller solar field (78 hc). This indicates the complexity of the optimization process. For the analysis of ethanol co-generation plant, the 7.5m-heliostat was considered since it provides consistently higher values of energy per direct cost for all power levels. Table 1 shows the configurations and results for heliostat size 7.5 m. Heliostat field configuration for power level 80 MW is shown in figure 4 as an illustration.

From production data provided by ethanol plant for the harvest year of 2014, average values for electric-energy generated per biomass and per day were estimated as 0.35 MWh/Ton and 620 MWh, respectively. Those values were obtained considering only months when production occurred in full, in other words, desregarding the first (April) and last (December) months of the harvest season. A maximum possible energy generation for each month were calculated by multiplying the average electric-energy generated per day by the days in the month. The heat input from the CSP system was estimated considering the electric energy output calculated by SAM with a power cycle efficiency of 0.37. The biomass savings for each month attained with the addition of the solar system was calculated by the solar-system heat input and a sugar-cane bagasse heating value of 7,600 kJ/kg (Perea and Teixeira, 2006). If the amount of bagasse produced added to the savings from the heat input of the CSP system was able to generated more energy than the maximum allowed for the month, bagasse were stored.

Table 1- Configuration and results for heliostat dimension of 7.5 m, which were used in the energy-generation of the cogeneration ethanol production plant

| Nominal Power Level [MW] | Heliostat size [m] | Tower Hight [m] | Area [hc] | Direct Costs [Mil U$] | Annual Energy [MWh] | Energy/Direct Cost [MWh/Mil U$] |
|---|---|---|---|---|---|---|
| 40 | 7.5 | 78 | 107 | 62 | 36454 | 588 |
| 50 | 7.5 | 103 | 107 | 81 | 43137 | 535 |
| 60 | 7.5 | 103 | 142 | 91 | 54588 | 602 |
| 70 | 7.5 | 103 | 188 | 100 | 65769 | 658 |
| 80 | 7.5 | 127 | 164 | 117 | 72914 | 623 |

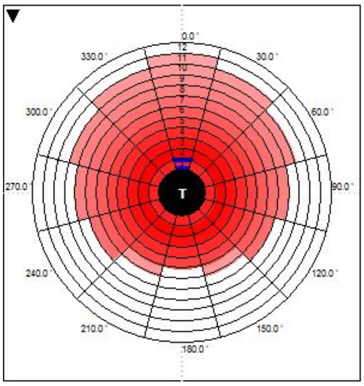


Figure 4. Solar field layout for power level 80 MW. Tower is at center and color intensity denotes heliostat density. Arrow indicates solar radiation coming from the north (figure from SAM)

Figures 5 and 6, shows the bagasse stock and energy generated for each month as function of time since the beginning of the harvest season, respectively. As expected, the biomass stock scaled with power level of the solar field. The maximum stock through the season was around 65,000 Ton of bagasse. This is an important value because logistics has to be considered for operational planning. The solar system was able to sustain the co-generation plant at full capacity for 4 months beyond current operation when compared to no solar system, except for the 40 MW configuration.

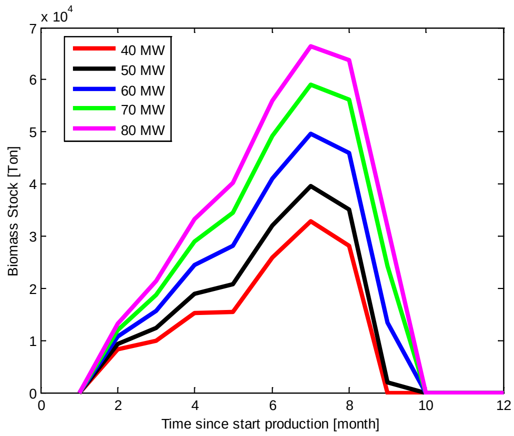


Figure 5. Sugar-cane biomass stocked as a function of time since harvest season beginning

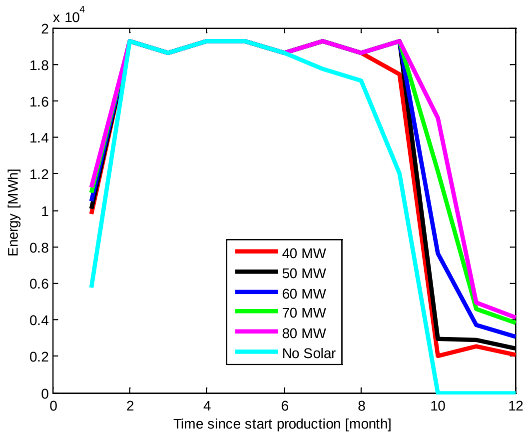


Figure 6. Monthly energy generation as a function of time since harvest season beginning

Table 2 shows total energy generated for the plant for the year 2014 for the different solar-system configuration. The energy-generation gain by the CSP system was estimated to be up to 26% in the year, which is a relevant contribution. Figure 7, shows the yearly energy generated as a function of the solar field area. It is remarkable that power level of 80 MW configuration yield more yearly energy with a less intense land use.

Table 2 - Energy generation results from the combination of CSP system with the existing plant

| Nominal Power Level [MW] | Energy [GWh/year] | Energy gain [GWh] | Increment [%] |
|---|---|---|---|
| 40 | 166,79 | 17,61 | 12 |
| 50 | 170,51 | 21,32 | 14 |
| 60 | 177,09 | 27,91 | 19 |
| 70 | 183,71 | 34,53 | 23 |
| 80 | 187,57 | 38,38 | 26 |

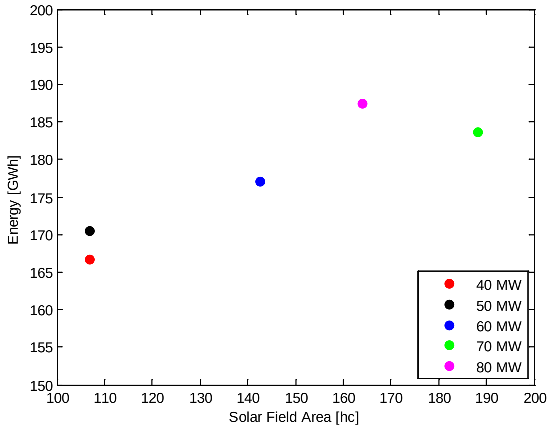


Figure 7. Energy production as a function of solar field area for different power levels

## 4. CONCLUSIONS

In this work, a case study of combining a central-tower CSP system with an existing ethanol-production cogeneration power plant was investigated. To estimate total heat input from the CSP system, the SAM platform was used to provide different solar-system configurations. The additional heat was considered as supplement energy for the vapor generation to power steam turbines. With the CSP system, sugar-cane bagasse could be stored to be used in off-harvest season and increase yearly electric-energy yield.

Five different solar field configurations were included varying the power level input in SAM. Tests were made to find best heliostat size for each power level given that SAM optimizes solar-field configuration based on heliostat dimensions. Results show that the hybrid arrangement is promising with annual electric-energy increased by up to 26%, taking advantage of the existing power-generation infrastructure, extending its operation beyond harvest season. Best configuration was for simulation power level of 80 MW with heliostat dimension of 7.5 m if land area is an issue for the installation, which might be the case for existing ethanol production plants. Otherwise, if land area is not a limiting factor, configuration provided by the 70 MW power-level simulation might be better in terms of direct costs per energy produced. It is important to remember that the power level in this case is just an SAM-input variable to get solar-field configuration.

The investigation done here is prospective, and is intended to evaluate the hybrid sugar-cane biomass - CSP solution. It also serves to guide best CSP configuration for this purpose. To get better estimates of energy production, a full thermodynamic cycle simulation is required. This is currently being done.

## 5. ACKNOWLEDGEMENTS

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