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INTEGRATION OF A CONCENTRATED SOLAR POWER PLANT, A BIODIGESTION PLANT AND A SUGARCANE BIORREFINERY

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Abstract. Electricity generation by solar hybrid power plants and sugarcane biorrefineries cogeneration systems are separated processes with a high potential for integration. Biorrefineries are already energetically self-sustainable but still allow big improvements, that take time due to the high life time of its current machinery. Ethanol production from cellulosic combings (as the sugarcane bagasse) and the vinasse biodigestion are examples of improvements directed to a better energy utilization of sugarcane. Both processes are not used yet in brazilian biorrefineries. The energy spent in the plants come from the bagasse, that is burned in a cogeneration process of vapor (used in the plant) and electric energy, also used in the plant and whose surplus is sold for the local public power grid manager. This work analyses the integration between a Concentrated Solar Power (CSP) plant and an ethanol production plant. The union of solar power plants and a burning fuel increases the economic viability of the whole business and the energy production reliability. A great source of biofuels like biomass and biogas is present in a sugarcane biorrefinery, with first and second generation ethanol production, biogas production from vinasse biodigestion and biogas and bagasse being burned to generate vapor in a combined system with the CSP plant. For that, data from an optimized biorrefinery were collected. These data include energy and biomass production per ton of sugarcane. A configuration and location were selected, for which solarimetric data, dimensions and components characteristics were collected. The integrated plant was sized considering both scenarios of maximum ethanol production and maximum electric energy exported to the grid, in order to maintain a constant operation twenty-four hours a day during the whole year. The solar plant was simulated in the software Ebsilon along the year with input measured irradiation data, in steady state intervals of 30 minutes. With the optimized solar field dimensions, the simulation attested to the integration viability, that avoids a thermal energy storage (TES) within the CSP plant. Event without the need of a TES, the coupling of a storage system to the integrated plant would allow the hybridized solar plant to be bigger and without wasting part of its peak steam generation periods.

Keywords: CSP, sugarcane, bioethanol production, vinasse biodigestion, cogeneration

INTRODUCTION

The sun is a primary energy source on which human life depends. Systems to convert sun light and heat to electricity have been largely studied. Photovoltaic cells are more feasible to use in residences, being smaller and converting light directly to electricity. For power plants, there are more sofisticated systems that absorb the sun irradiation heat with a heat transfer fluid, and then use this heat in an industrial process or to generate power in a thermodynamic cycle, what gives to those plants the name of solar thermal power plants.

Great amounts of energy production can be derived from the sun between the tropics, where there are the most sunny regions. For this reason, even in an almost self-sustainable country like Brazil, leading positions in sugarcane ethanol production and hydro power energy generation, a technlgy boosting for the energy sector is expected in the near future. A big share of this development depends on technical and economic assessment of building and operating solar plants in brazilian regions, and more than that the adaptation assessment of existing power plants so that they become more self-sustainable adding solar systems.

To adapt current operation systems, energy from different sources can be combined, in order to overcome deficiencies related to each. One of such approaches is the hybrid solar electricity generation. It joins the solar energy and the energy generated by burning fuels, that is cheaper. This union comes with a series of benefits, as costs reduction, dispatchability increase, used area reduction and increase of the economic viability. When biofues are used for that purpose, the energy does not loose its renewable character, and that is why the combination of good solar conditions and biofuels availability confers a great potential to certain regions in the world.

Since a few decades ago, biofuels have been boosted in brazilian economy due to green house gases (GHG) regulations, increase of pollution, the dependency of fossil fuels, and mostly the sugarcane harvesting proper conditions of Brazil. The current biofuels production tends to increase, causing a migration of the sugarcane plantations to forests, low land availability and consequent prices increase. That arouse all over the world interest in ethanol production from cellulosic combings (as the sugarcane bagasse). Called second generation (2G) bioethanol, its production in large scale is beeing studied by mane researchers. (Leite and Leal, 2007; Nyko *et al.*, 2010).

Both first generation (from sugarcane broth) and second generation ethanol (1G and 2G) produce a lot of vinasse (approximately 10 liters per ethanol liter), liquid combing generated by the ethanol distillation. This biorrefinery effluent can become an environmental problem depending on its destination. A possible end for it is the anaerobic biodigestion to produce biogas, once vinasse has a high organic content. (Moraes *et al.*, 2014; BNDES and CGEE, 2008).

The current technologies give energetic self-sufficiency to the refineries, that sell its exceeding energy to the public power grid manager, but a more efficient energy use still depends on studies to choose a better destination to the vinasse. Besides that, almost all the refineries in Brazil generate all its exceeding energy in the season period, that corresponds to approximately two thirds of the year, and generation systems stand still throughout the off-season period. As alternative for that, the bagasse from 1G process and the straw can be used to produce 2G ethanol, and the vinasse resulting of 1G2G production can be used to produce biogas. This biogas can be burned to generate vapor to the refinery processes, supplying the lack of bagasse, or generating electric energy to the grid, or still to hybridize a solar power plant.

Solar plants don't supply constant power to the grid by itself, needing a fuel to be burned together with the plant operation or a thermal storage, aspects that would be improved by burning the available biofuels to generate steam and control steam turbines power output. Besides that, a CSP-biomass hybrid plant has an investment up to 69% lower than an only solar plant. Considering not only advantages to the solar plant, the biogas production system implantation from vinasse has a return from the investment of over ten years, what would be decreased with the integration (Peterseim *et al.*, 2014)

CSP plants must have an installed capacity of at least 50MW. In contrast, the capacity of biomass-based plants is limited to 50MW because of the transport cost, and must be at least 5MW to be profitable. Smaller plants are possible (2MW-10MW) in the case of trigeneration systems. Up to 50% reduction in costs has been noticed in hybrid systems compared to exclusively CSP systems, although it is still a higher cost than exclusively biomass systems. Not only as a way of producing and selling electric power, hybridization is also a way of selling carbon credits, granted by regulatory bodies to companies around the world for these and other initiatives that save the emission of greenhouse gases (Pramanik, 2017).

According to Peterseim *et al.* (2014), what best suits a CSP without thermal storage is the DSG (Direct Steam Generation) technology. In view of the better use of waste from ethanol refineries and the confirmation that solar plants have the potential to take advantage of the integration with a refinery, the present work evaluates such integration between a sugarcane biorrefinery, an annexed biodigestion plant and an annexed DSG solar plant, for the vinasse biodigestion and use of bagasse and biogas in an integrated steam and power generation with a Rankine cycle. With models of a DSG solar power plant implemented in the software Ebsilon, this work simulates the solar plant variable operation over the year, considering a steady state operation in each time interval simulated. Having collected data of an optimized refinery, the amount of bagasse is updated with the steam mass flow required to hybridize the solar plant and the refinery ethanol production at each time interval.

INTEGRATION STUDIES

Manochio (2015) assumes that the production of second generation ethanol (2G) is an alternative to increase the productivity of bioethanol in biorefineries that in Brazil, until then only produce 1G ethanol and burn the bagasse for energy plant. By maintaining the same area of cane planted, aggregating 2G production, and producing biogas from the vinasse is a source of heat to generate steam for the plant's processes, and ethanol production increases. According to the data collection and analysis of production in Brazil per ton of sugarcane, a production of 23 L of second generation ethanol per ton of sugarcane was estimated without compromising the efficiency of the processes. Likewise, 9.82 m³ of methane per ton of sugarcane can be produced by the biodigestion of the vinasse. Optimizing the production of ethanol without lacking energy for the internal processes of the plant, it was estimated that 17% of the bagasse can be transferred from the burning to the production of 2G ethanol. In addition to quantitative results, the author cites increased productivity, reduction of environmental impacts of vinasse in the soil, prevention of emissions of about

33,000 t of N2O, increase in annual revenue and sale of carbon credits, which could cost the operation of biodigestion in the unit.

Restrepo (2014) studies the coupling between a thermosolar plant with Linear Fresnel Reflectors and Direct Steam Generation to a cogeneration plant in the sugar-alcohol sector of Mato Grosso as a way to increase the efficiency of the units. The plant is equipped with steam generating units by burning bagasse from the plant. In order to use solar energy to heat the feed water from the steam generators, bagasse consumption is reduced during the harvest, and stored to be burned in the off season, and the production of increased electrical power throughout the year. A thermodynamic model was created in the EES, taking as input variables the collector area, the optical efficiency of the solar field, and the exit temperature of the water in the solar field. It was possible to calculate the conversion efficiency of the irradiation in electricity, the increment of electricity generation of the plant and the percentage of fuel economy obtained for different solar multiples, and for different degrees of water heating. In the best case, the simulations showed the production of 270.65 GWh of surplus electric power with the processing of 3,300,000 tons of cane per year.

Bertin (2017) sized a solar plant using a Solar Tower receiver for Direct Steam Generation and combination with an ethanol plant in São Paulo to save bagasse throughout the harvest and burn it in the off season to extend the period of electricity generation . He simulated the solar field from the solarimetric data for the region, to optimize the heliostat layout and size the field. Simulated the SAM solar power system to optimize solar multiple, energy level cost, capacity factor and achieve energy performance. The configuration of the system varied between 30% and 100% of the energy generated from the bagasse during different periods of the year and day. He concluded that the hybridization of the system would enable power generation 24 hours a day, and the optimized system has an operating capacity of 8,000 hours per year, double the current capacity. This was achieved with a solar field of 1,070 heliostats occupying an area of 73 hectares, a 30-year useful life, and an investment return rate of 11% per year.

METHODOLOGY

Configuration

The refinery configuration proposed is the same of the work of Dias (2012), from where the refinery steam generation data were taken. In her work, a cogeneration power plant was improved, elevating the boiler pressures and replacing the mechanical drivers by turbo generators and electric motors to calculate two scenarios: maximize the electricity production and maximize the second generation ethanol production. When maximizing the electricity, no 2G ethanol is produced, because all the bagasse is burnt. When maximizing the 2G ethanol production, some surplus electricity is still produced, due to the biomass resultant from the 2G process, that corresponds to an estimate of 66% of the bagasse hydrolized energy (Dias, 2012; Manochio, 2015)

The refinery layout is presented in Fig. 1. It is composed by a back pressure steam turbine (BPST) and a condensing-extraction steam turbine (CEST). Both the turbines receive steam at the boiler pressure (90 bar), but the BPST discharge steam at 2.5 bar to the refinery processes while the CEST discharge steam at very low pressures to the steam condenser. In this work, only the steam generation is maximized, to increase its capability of hybridizing a solar power plant and, consequently, of exporting the maximum electricity for the public grid.
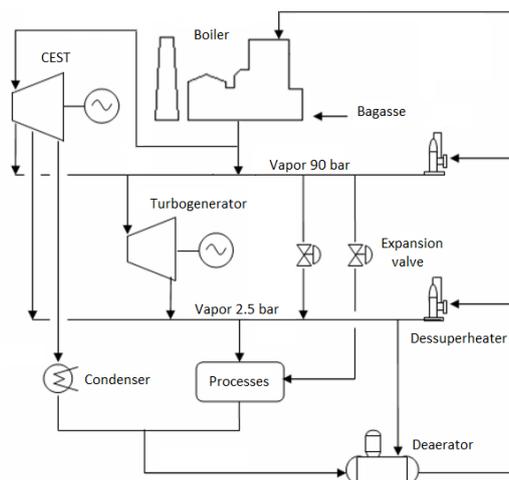

Figure 1. Model of the biorrefinery cogeneration plant
Source: Adapted from Seabra *et al*. (2008)

The configuration proposed to integrate the refinery is a DSG parabolic trough collectors field, and its layout is presented in Fig. 1. The layout is composed of an evaporation section and a superheating section, divided by steam separators in each line. Each section has lines of PTC collectors in parallel, all of them oriented in north-south direction. The model ET-100 with absorber tubes of the model PTR70 were chosen based in other works (Zarza *et al.*, 2006). Only one line of collectors is represented in each section, with a random number of collectors.
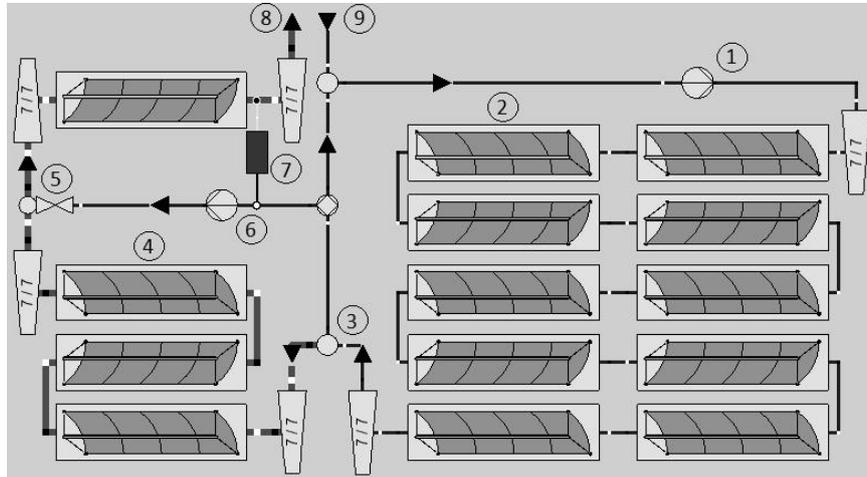

Figure 2. Model of the DSG solar power plant. 1) Feed pump. 2) Evaporation line. 3) Steam separator. 4) Superheating line. 5) Water injector. 6) Injector pump. 7) Temperature controller. 8) CEST. 9) Deaerator.
Source: Adapted from Ebsilon interface

The collectors operate recirculating all the liquid not evaporated in the evaporation section immediately to the beginning of the evaporation lines. This strategy has been chosen, because it is proven a good way of controlling the steam quality at the end of the superheating lines (Eck *et al.*, 2003).

The plant has control systems, such as the collector tracking system, the steam temperature control and the saturated steam quality control. The tracking system position the trough rotating it in the north-south axis along the day. The steam temperature control is promoted by a water injector located before the last collector of each superheating line. The steam quality control is promoted at the evaporation lines outlet varying the feee mass flow, that is the incoming water flow that mixes with the recirculated flow before the evaporation lines.

The solar plant and the refinery share the CEST turbine and the rest of the block of power (condenser, deaerator, etc.). So, the steam discharged to the CEST turbine is the sum of the refinery steam not used in the electric drivers and the steam generated by the solar collectors. A main assumption here is the totally variable operation of the refinery boiler.

The season period is also from the work of Restrepo (2014) and lasts from April 1st to December 7th. During this period, bagasse from the production is introduced second to second in the calculation, in order to be stored or to be burned, according to the solar irradiation.

Refinery data collection

Data were collected from different authors using a methodology similar to Manochio (2014). The difference from this author is that her work didn't consider the solar aided steam generation, but only the maximization of the 1G2G ethanol production to generate the exact steam required by the process.

Table 1. Refinery production values collected from many authors, and selected refinery operation data.

Refinery configuration	Without biodigestion	With biodigestion	Source
Effective harvest operation time (hours)	5,000.00	5,000.00	Restrepo, 2014
Effective harvest operation time (days)	251.00	251.00	Restrepo, 2014
Sugar-cane processing capacity (t/h)	500.00	500.00	Dias *et al.*, 2012
Process steam consumption (kg/t)	317.00	557.00	Dias *et al.*, 2012
Overall steam production (kg/t)	903.00	621.00	Dias *et al.*, 2012

The chosen location is Belo Horizonte, in Brazil, because of its good solar conditions, solar measurements available for the analysis, and weather not so different from regions with well stabilished sugarcane plants. To calculate solar radiation and incidence angles, data in Tab. 2 is necessary.

Table 2. Geographic location and solarimetric data

City	Belo Horizonte
Latitude {N+/S-}	-19.8157
Longitude {E+/W-}	-43.9542
Time zone {+/- GMT}	-3
Altitude {m}	767

Solar plant modeling and simulation

The incidence angle of the solar irradiation on the parabolic troughs are calculated based in an approach of Duffie and Beckman (1991), according to the local time, date, latitude, and longitude. given by Eq. (1) (Steag, 2018).

Once the irradiation normal to the collector is calculated, the effective irradiation received by the collector is given by Eq. (2), and the heat loss through the whole absorber tubes length is given by Eq. (3) (Steag, 2018).

$$Q_{effective} = DNI_{op}\eta_o ACFSLBW - Q_{loss} = \dot{m}(h_o - h_i) \tag{1}$$

$$Q_{loss} = 0.0047(dT)^2 \tag{2}$$

Where DNI_{op} is the normal irradiance to the collector, A is the effective opening area of the collector, η_o is the optical efficiency of the collector, C is the correction value of the angle of incidence, F is the focusing factor, S is the shadow factor, L is the cleaning factor of the mirrors, B is a reflection loss factor at the edges of the collector, W is a factor of optical losses due to the impact of the wind, Q_{loss} is the heat loss, $\dot{m}$ is the mass flow of the solar field, and h_i and h_o are the enthalpies of the inlet and outlet fluid of the solar field. $Q_{effective}$ represents the effective heat received by the fluid throughout the collectors line. dT is the difference between fluid temperature and ambient temperature (Steag, 2018).

Pressure losses are calculated by a correlation of Friedel *et al*. (1979) for biphasic flows and a correlation of Swamee *et al*. (1976) for single-phase flows. Even when a biphasic flow is calculated, the two correlations are used. For the single-phase correlation, the pressure loss is calculated as the sum of losses of each phase. The biggest calculated pressure drop between Friedel *et al*. (1979) and Swamee *et al*. (1976) is adopted (Steag, 2018).

Having the refinery production values and the solar plant models implemented in the software, the solar plant is simulated. First, simulations of only one line of evaporation collectors and one line of superheating collectors are done. Then, after the solar plant behavior is understood, the maximum CSP plant for which the biofuels are enough to maintain a constant steam generation along the whole year is sized. Preliminar calculations are done in a spreadsheet, where output values change instantaneously with the simulation process. The simulation considers the amount of biofuels burned and solar irradiation in steady state intervals of 30 minutes along the year.

RESULTS

To size the solar plant, a basic calculation gives the steam mass flow exceeding the refinery demand that can be produced, shown in Tab. 3.

Table 3. Steam mass flow available in the refinery

Refinery configuration	Without biodigestion	With biodigestion
Total cane processed per day (t/day)	12,000.00	12,000.00
Steam mass flow per second (kg/s)	81.39	8.89

If that amount of steam can be constantly produced in a reliable way, with no unforeseen process stops, a power plant can be sized for each situation using those steam mass flows. If a solar power plant is integrated, there must be an optimized solar field size for which there is always bagasse and/or biogas to be burned, and capable of generating the maximum steam mass flow constantly.

To find this optimal solar field size, the number of collectors per evaporation line and per superheating line are varied, and simulations present the results shown in Tab. 4. Both the sections require lines limited in size. The superheating and evaporation lines size are limited superiorly by the pressure loss in high mass flow rates, that happen

in high irradiation values. The superheating line size is limited inferiorly by the maximum incoming saturated steam mass flow at each direct normal irradiation in order to control the temperature of the outlet superheated steam mass flow. The evaporation line size is limited inferiorly by the damage resultant of small mass flows, that happen in low irradiation values.

Table 4. Variation of the number of collectors in a combination of one evaporation line and one superheating line at the DNI of 800 W/m^2

Collectors per evaporation line	Collectors per superheating line	Superheated steam mass flow (kg/s)	Evaporation line mass flow (kg/s)
6	3	1.112418	1.243862
6	4	1.244656	1.243862
6	5	1.362633	1.243862
7	4	1.257949	1.266819
7	5	1.376858	1.266819
8	3	1.129944	1.275559
8	4	1.262999	1.275559
9	3	1.21825	1.43595
9	4	1.354774	1.43595
9	5	1.479529	1.43595
10	3	1.305935	1.596063
10	5	1.574046	1.596062

Each number of collectors per superheating and per evaporation line have a maximum mass flow, that dictates how many collector lines are gonna be necessary for each section. Using more shorter lines, instead of less longer lines, is justified if the same total amount of steam generated is got with a smaller total number of collectors. The choice of the lines size takes into account the superheated steam temperature control reliability and the minimum number of collectors being used in the plant, to decrease the investment.

Five steam mass flows are chosen and the number of lines to generate these values are calculated according to the steam produced by each line, in order to minimize the total number of collectors in the plant. The results of the five steam mass flows is shown in Tab. 5 and Tab. 6.

Table 5. Calculation of the minimum number of collectors in the superheating section for each steam mass flow

Superheated steam mass flow	Collectors per superheating line	Superheated steam mass flow per superh. line (kg/s)	Superheating lines	Total evaporation collectors
50	3	1.11	46	138
70	3	1.11	64	192
90	3	1.11	82	246
110	3	1.11	100	300
130	3	1.11	118	354

Table 6. Calculation of the minimum number of collectors in the evaporation section for each steam mass flow

Superheated steam mass flow	Saturated steam mass flow (kg/s)	Collectors per evaporation line	Saturated steam mass flow per evap. line (kg/s)	Evaporation lines	Total superheating collectors	Total collectors
50	45.597	6	0.995	46	276	414
70	63.440	6	0.995	64	384	576
90	81.282	6	0.995	82	492	738
110	99.125	6	0.995	100	600	900
130	116.967	6	0.995	118	708	1062

As can be seen, for all the steam mass flows, the minimum size of solar plant is achieved with evaporation lines of 6 collectors and superheating lines of 3 collectors, considering a design DNI of 800 W/m^2. With this selected dimension, the plant is simulated along the year of 2017. Figure 3 shows the calculated DNI incident to the collectors on March 3rd 2017, delayed in relation to measured data to represent the impact of the flow residence time

inside the absorber tubes over the effective heat transferred to the fluid. Not only delayed, the calculated DNI is decreased by the incidence angle modifier, the optical efficiency and the thermal efficiency.
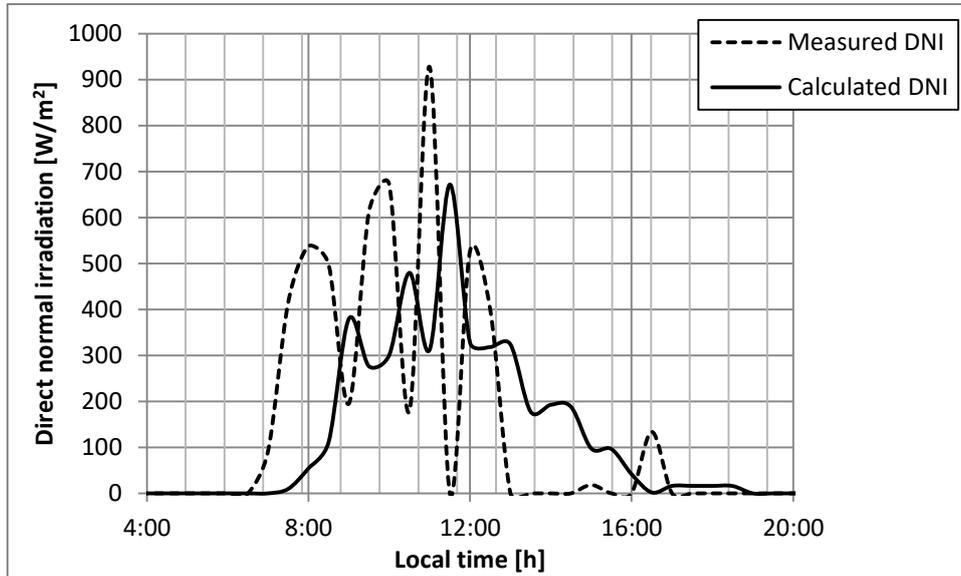

Figure 3. Direct normal irradiation measured data and calculation on March 3rd 2017

After that, the results of the simulation are used to calculate the maximum design steam mass flow that the integration can achieve, such that the bagasse and/or biogass are still enough for hybridizing the plant, being available to be burned and support the power plant operation throughout the year. Figure 4 shows the amount of biomass stored in the two scenarios.
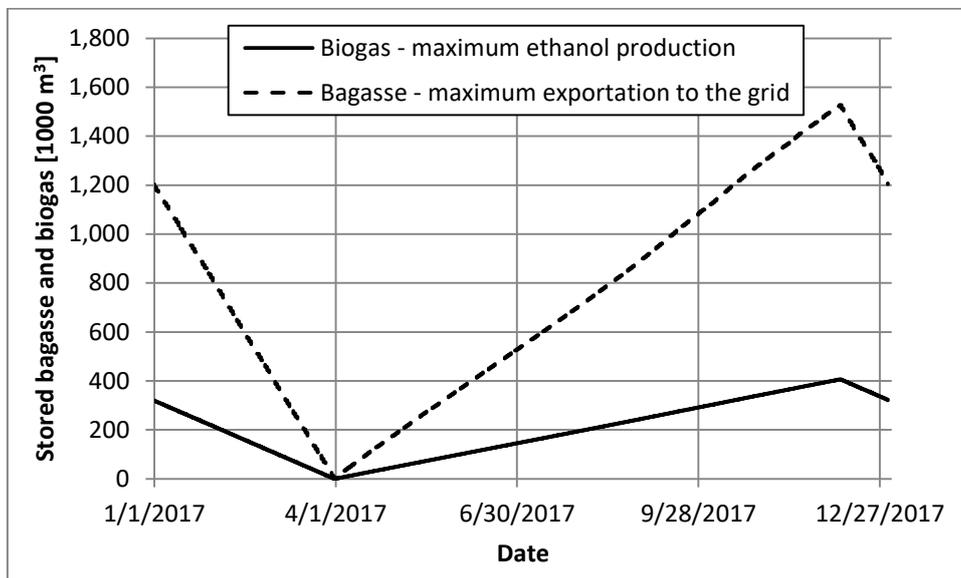

Figure 4. Amount of bagasse stored along the year

All the plant sizes with their different design steam mass flows showed approximately the same stored amount progressions over the year, for both scenarios. In the scenario where maximum ethanol is produced and considering the bagasse density as 100 kg/m^3 and the bagasse steam production as 2.25 kg/kg, around 1.5 millions of m^3 would be necessary to store bagasse in the integration. In the scenario where the electricity exportation to the grid is maximized and considering a methane steam production of 6.44 kg/m^3 and disconsidering the parcel of bagasse burned with the biogas, 0.4 million m^3 would be necessary to store the biogas available.

After the simulations is replicated for different design steam mass flows, the chart of Fig. 5 is built. It shows how, even increasing the designed solar plant, the constant steam generated by the integrated plant over the year achieves a

stationary state. Knowing the integrated plant won't be capable of producing much more than 70 kg/s, the solar plant must be sized with the maximum design mass flow of 200 kg/s, corresponding to a solar multiple of 2.9. It is noted, as well, in both scenarios the maximum feasible steam mass flow to be constantly generated throughout the year is smaller than the steam produced by the standalone refinery itself. In the scenario 1, for example, 70 is smaller than 81.39 kg/s.

This is still not a feasible size for the solar plant if no TES is coupled to the plant. Solar multiples bigger than 1, for which the design steam mass flows is bigger than 50 kg/s imply automatically higher solar irradiation periods will produce steam mass flow higher than the turbine supports, and this thermal energy will need to be rejected. For a design mass flow of 200 kg/s, approximately 40% of the total solar thermal power is thrown away if no TES is used.

Figure 6 shows what a TES would mean to the plant. No heat would be wasted due to solar peak hours, and the solar fraction wouldn't be restricted to only 4% of the total thermal energy promoted by the bagasse.
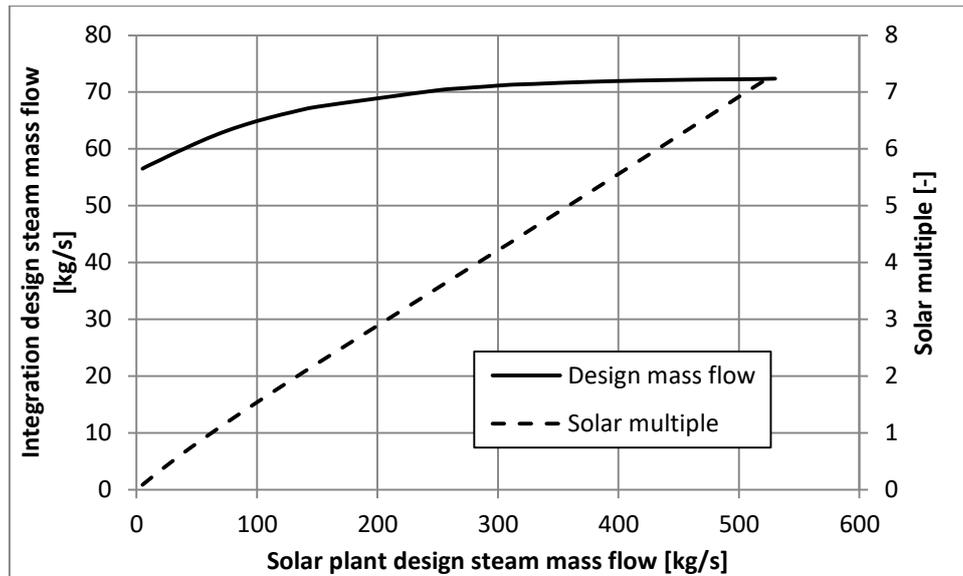

Figure 5. Maximum constant steam mass flow achievable by the integration and corresponding solar multiple
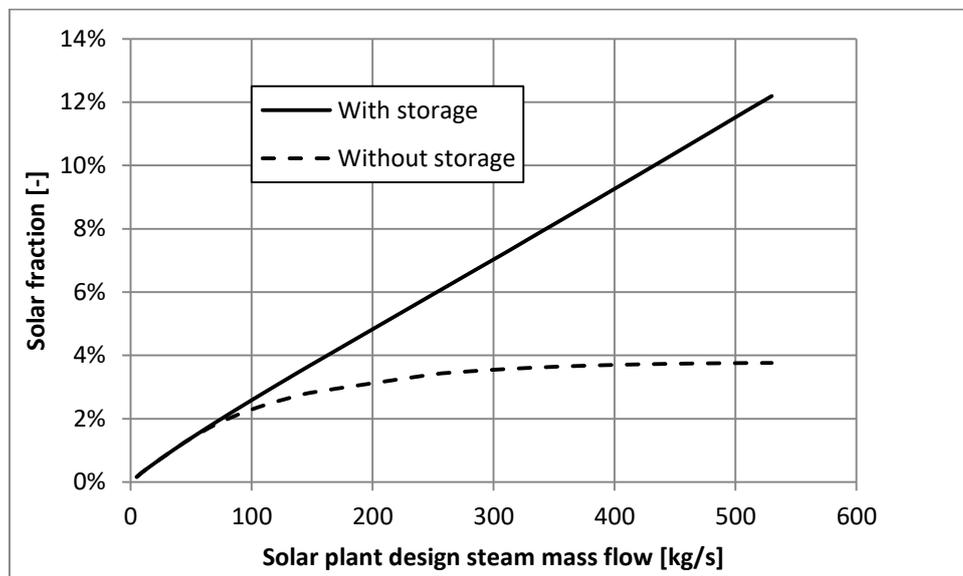

Figure 6. Fraction of thermal energy related to the solar plant for two cases

For an integrated plant in the scenario 2, when the maximum ethanol is produced, the charts look similar, and the solar fraction tend to the same value. If it is intended that a TES be coupled to the plant, the TES size is the new limitant of the solar fraction, and no more the heat rejected in high irradiation periods.

CONCLUSION

The work concludes that ethanol biorrefineries can consider to check future notices of application to extend their electric energy exportation to the public grid by building solar and biodigestion annexed plants. The cost of producing energy for a DSG plant is decreased by the biofuels source, that makes an expensive thermal storage unnecessary in the plant.

Apart from that, the work concludes a TES can be considered together with the hybridization, because the solar fraction of the integrated plant is limited to 5% when no TES is used. Even bigger solar plants don't add much power generation increase in the integrated plant, solar fractions up to 10% can be considered only with the TES addition.

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