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**PERFORMANCE ASSESSMENT OF SOLAR-BIOMASS HYBRID  
COGENERATION CYCLE APPLIED TO THE CORN ETHANOL  
INDUSTRY**

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***Abstract.** This work presents the performance analysis of the solar thermal hybridization of a typical biomass cogeneration cycle used by corn ethanol plants. A direct steam generation (DSG) parabolic trough solar field is considered as Concentrated Solar Power (CSP) technology and applied in parallel with the boiler on a fuel-saving operation strategy. The Epsilon Professional is considered as the computational tool for the performance assessment and comparison of the cycle energy efficiency and fuel saved in a typical meteorological year on an hourly basis. The results show the technical feasibility and possible advantages of applying CSP technology to the cogeneration of corn ethanol plants.*

***Keywords:** corn ethanol production, solar-biomass hybrid cogeneration, concentrated solar power, direct steam generation*

## 1. INTRODUCTION

Through the different sectors, transportation is one of the biggest energy consumers there is. According to the International Energy Association (IEA), it represented 30 % of all energy consumed in 2017 (IEA, 2019). However, as the world puts effort into changing to a cleaner and more renewable energy matrix, non-fossil sources of fuel like bioethanol stand out as an alternative. Brazil is the second-largest fuel ethanol producer accounting for 32,441 dam<sup>3</sup> of ethanol or 30% of the global production in 2019 (RFA, 2019).

Until recently, for historical, geographical, economic, and technological reasons, the ethanol manufactured in Brazil came only from sugarcane. However, in the last few years, the low levels of corn price in the central-west region, caused by the booming of corn production and the difficulty to outlet this production, made viable the installation of a fast-growing corn ethanol industry in the country. The first attempts of corn ethanol in Brazil started through the adaptation of sugarcane mills to produce corn ethanol in off-season periods in what is called flex plants. Later came the full corn ethanol plants (Eckert et al., 2018).

Corn ethanol plants are intense consumers of process heat and electricity; thus, they can benefit from the use of cogeneration. A typical corn ethanol plant in the USA may consume 9.67 MJ of process heat and 0.288 kWh of electricity per liter of ethanol produced (Mani et al., 2010). These energy consumption levels are usually lower than the ones present in sugarcane ethanol plants. Nonetheless, when looking at the primary source of energy for the plant processes, there is a relevant difference between producing ethanol from sugarcane and corn. While the sugarcane has the bagasse as a coproduct, which can be burnt in the boiler as plant fuel, the corn ethanol plants need to use external fuel sources like coal, natural gas, or wood, which in turn makes its operation more expensive (Nogueira, 2014).

Researchers have proposed different routes to solve the external fuel source issue. Karupiah et al. (2008) focused on the plant design, optimizing the thermochemical processes to reduce overall energy requirements. Morey et al. (2006), Tiffany et al. (2008), and Wang et al. (2009) analyzed the viability of using the corn ethanol coproduct dried distillers grains with solubles (DDGS) and corn stover as fuel. Kam et al. (2009) examined the use of DDGS and stover but comparing their direct combustion in a biomass boiler and their gasification for later combustion.

Another way to approach the presented problem is by using solar energy to inject heat into the cogeneration cycle. Concentrated Solar Power (CSP) is a renewable energy technology that can be used by corn ethanol plants to help to deal with the external fuel expenditure. CSP collectors can be applied to heat the desired fluid, by concentrating direct solar

irradiation (DNI), to drive a turbine or feed a heat-consuming industrial process. Between the different CSP technologies, Parabolic Trough Collectors (PTC) stand out for being the most mature concentration technology and for having higher optical efficiency than other linear collector types. The PTC typically use synthetic oil as heat transfer fluid, transferring the acquired heat to the steam cycle through a heat exchanger at a maximum temperature of 400°C (Fuqiang, 2017). Brunet et al. (2014), for example, analyzed the applicability of such a concept in the indirect heating of the distillation tower of a corn ethanol plant. On the other hand, the PTC can also operate on Direct Steam Generation (DSG), heating water directly and generating steam with temperatures up to 500°C (Giglio et al., 2017). While studies like Burin et al. (2015) dived into the use of CSP technology to preheat feedwater in a sugarcane ethanol plant, no investigations regarding the use of CSP solar fields to directly generate steam to corn ethanol plants were found.

Given the scenario outlined, this work presents the performance assessment of a solar-biomass hybrid cogeneration cycle for a typical corn ethanol plant that produces yearly 264 dam<sup>3</sup> of ethanol. A PTC solar field in DSG is used in parallel to a biomass boiler to feed the plant's needs. The analysis focus on the evaluation of the cycle energy efficiency and biomass saved for a typical meteorological year, on an hourly basis, for a location in Brazil. Also, this paper analyzes the off-design performance of the boiler, to show the effects of the boiler operating simultaneously with the solar field, and the area of eucalyptus plantation not needed anymore by the use of the solar field.

## 2. METHODOLOGY

### 2.1 Cogeneration cycle description

The proposed hybrid cogeneration cycle is illustrated in Fig.1. It follows the general description made by corn ethanol engineering companies of a typical plant steam cycle to which parabolic trough collectors were connected. The superheated steam generated by the boiler and solar field is fed to a Back Pressure Steam Turbine (BPST), at 6.7 MPa and 520°C, from which the steam leaves at two different pressure levels. The first pressure level is destined to feed the DDGS drier at 0.8 MPa and the steam flow at the second pressure level is used for all other production processes at 0.15 MPa. The proposed cycle doesn't have a condenser but rather condensates the steam by the end of the different ethanol plant processes. The condensate goes through a steam trap after which flash steam is generated. All flash steam is released to the atmosphere, and the condensate follows to the deaerator. Before reaching the deaerator, the condensate, now at atmospheric pressure and 80 °C, is pumped to the deaerator pressure of 0.2 MPa. At the deaerator, make-up water is added to the cycle to compensate for the lost flash steam. Finally, the condensate that leaves the deaerator is pumped back to the boiler and solar field at 6.7 MPa.

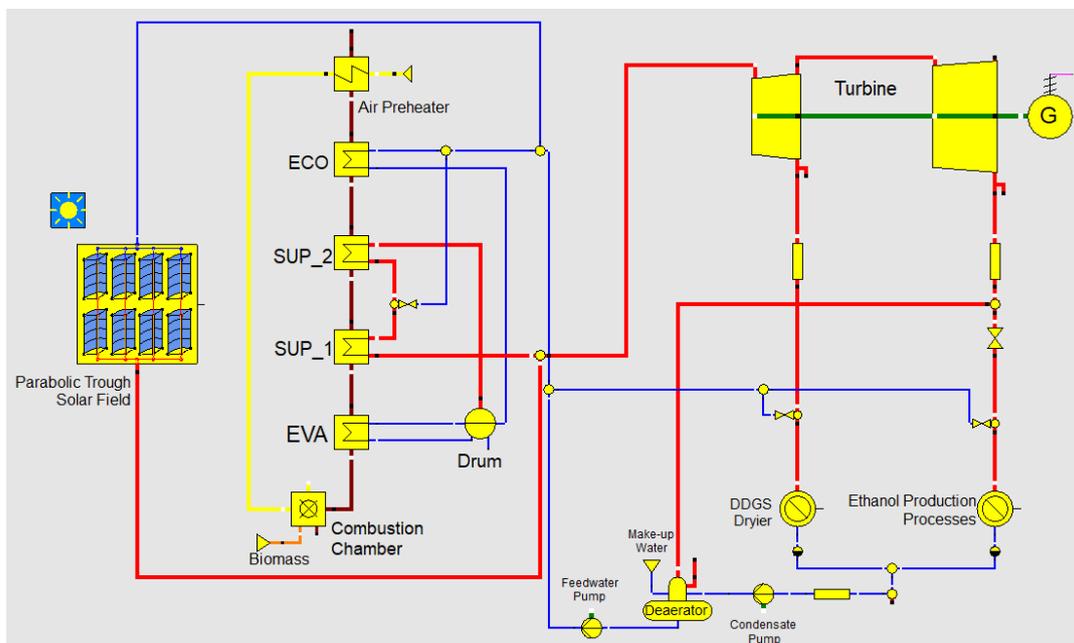


Figure 1. Schematic of the modeled solar-biomass hybrid cogeneration plant

The plant modeled produces 264 dam<sup>3</sup> of ethanol yearly (0.8 dam<sup>3</sup> daily). For this production level, 12.5 kg/s of steam, at 0.8 MPa, is needed for the DDGS drying process and 37.5 kg/s, at 0.15 MPa, is needed for the other ethanol production processes. The biomass used in the boiler is wood chips of eucalyptus. The eucalyptus chips net calorific value (NCV) of 12747.07 kJ/kg was calculated via the Mendeliev formula as described by Cortez et al. (2008). The wood elementary

composition considered can be seen in Tab. 1. This is a reference composition obtained by consulting a Brazilian boiler company. Finally, the PTC solar field uses the Eurotrough concentrators on a once through design.

Table 1 – Eucalyptus wood elementary composition in wet basis

Element	%
C	35.00
H	4.67
O	29.40
N	0.11
Ash	0.82
Humidity	30.00

The main parameters of the different cycle components can be found in Tab. 2.

Table 2 – Plant component's main parameters

Component Parameter	Value
Boiler air ratio <sup>(1)</sup>	1.50
Boiler slag temperature, °C	400.00
Boiler fly ash ratio	0.30
Boiler combustion efficiency	0.99
Boiler radiation heat losses factor <sup>(2)</sup>	0.02
Evaporator global heat transfer coefficient, kW/K	99.02
Superheater 1 global heat transfer coefficient, kW/K	70.01
Superheater 2 global heat transfer coefficient, kW/K	13.42
Economizer global heat transfer coefficient, kW/K	41.18
Air preheater global heat transfer coefficient, kW/K	290.10
Turbine high pressure section isentropic efficiency	0.85
Turbine low pressure section isentropic efficiency	0.88
Generator efficiency	0.98
Pump isentropic efficiency	0.80
PTC collector length, m	150.00
PTC gross aperture width, m	22.00
PTC optical active aperture area factor	0.95
PTC Row Spacing, m	17.28
PTC peak optical efficiency	0.75
PTC mirror cleanliness factor	0.95
PTC tuning factor shading model	1.00
PTC tuning factor optical end loss	1.00
PTC tuning factor optical end gain <sup>(3)</sup>	0.50
PTC constant piping heat loss, W/m <sup>2</sup>	20.00

<sup>(1)</sup> to stoichiometric air

<sup>(2)</sup> relative to the total energy released in the combustion

<sup>(3)</sup> considering four collectors in a row in a U-type arrangement

## 2.2 Modeling and simulation

The approach used in the study is to calculate the plant performance hour by hour through a typical meteorological year. The operation of the plant follows the fuel-saving strategy. In this strategy, the sum of the steam generated by the solar field and by the boiler is equal to the nominal operation requirements of the plant, which means that, as the irradiation levels available increase, the boiler needs to generate less steam, working on a part-load regime. Furthermore, the location chosen for the proposed plant is the city of Barreiras-BA (-13,27°, -43,35°) in Brazil. Besides being a corn-producing center, Barreiras has favorable levels of irradiation.

For the modeling, the following simplifying assumptions were taken:

- (1) Steady state flow (in each hourly time step);

- (2) Heat exchangers are adiabatic and work on countercurrent flow;
- (3) Heat losses by purges were disregarded;
- (4) All flash steam generated is lost to the atmosphere and is restored as make-up water in the de-aerator;
- (5) The boiler air ratio is constant

Equation (1) is used to calculate the number of collectors in the solar field considering that the solar field delivers at maximum 60 % of the steam load. In this equation,  $N_{coll}$  is the number of collectors,  $P_{FL}$  is the power the boiler delivers at full-load,  $DNI_{ref}$  is the reference irradiance,  $A_{net}$  is the net collector aperture area,  $KIA$  is the incident angle correction (cosine losses already included),  $\eta_{peak}$  is the peak optical efficiency,  $\eta_{shading}$  is the shading loss factor,  $\eta_{endloss}$  is the endloss loss factor,  $\eta_{clean}$  is the cleanliness factor, and  $Q_{loss}$  is the power loss in the absorbers and piping of the solar field.

$$N_{coll} = \frac{0,6 \times P_{FL}}{(DNI_{ref} \times A_{net} \times \eta_{peak} \times KIA \times \eta_{shading} \times \eta_{endloss} \times \eta_{clean}) - Q_{loss}} \quad (1)$$

The cycle energy efficiency is calculated using Eq. (2). In this equation,  $\eta_{peak}$  is the cycle energy efficiency for a given period,  $Q_{th,process}$  is the process heat used in the producing processes,  $Q_{EI}$  is the electrical energy produced in the generator's terminal,  $m_{biomass}$  is the mass of biomass burnt in the boiler,  $NCV$  is the net calorific value, and  $Q_{th,solar}$  is the thermal energy obtained through the CSP collectors.

$$\eta_{cycle} = \frac{\sum Q_{th,process} + \sum Q_{EI}}{\sum (m_{biomass} \times NCV) + \sum Q_{th,solar}} \quad (2)$$

The economized fuel, for a given period of time, can be expressed by Eq. (3) where EF is the economized fuel,  $m_{biomass,base}$  is the mass of biomass consumed by the cycle with only the boiler, and  $m_{biomas,solar}$  is the mass of biomass consumed by the hybrid plant. While the solar fraction ( $SF$ ), which represents the fraction of plant thermal demand provided by solar energy, is calculated via Eq. (3).

$$EF = \sum (m_{biomass,base} - m_{biomass,solar}) \quad (3)$$

$$SF = \frac{EF}{\sum m_{biomass,base}} \quad (4)$$

Finally, the area of eucalyptus forest ( $A_s$ ) in  $km^2$  required annually to meet the biomass demand of the plant is calculated according to Eq. (5) by considering a mean annual volume increment of energy forest plantation ( $MAI$ ) in  $m^3 km^{-2} year^{-1}$ . The other parameters in Eq. (5) are the power plant annual biomass demand ( $BD$ ), in  $kg/year$  and the biomass density ( $\rho$ ), in  $kg/m^3$ .

$$A_s = \frac{BD}{MAI \times \rho} \quad (5)$$

The intended performance assessment is done through modeling and simulation using the Epsilon Professional software, in the 14.03 version, with meteorological data from Meteororm software.

### 3. RESULTS

The base case and hybrid cogeneration plant's design point performance result parameters can be seen on Tab.3. The number of parabolic trough collectors and the hybrid plant's design point were obtained via the calculation of the parameters in Tab.4 considering a reference irradiance of  $950 W/m^2$ , at the noon of the 22<sup>nd</sup> of December, a ambient temperature of  $24 ^\circ C$  and a wind speed of  $3,15 m/s$ . Both the ambient temperature and the wind speed used are annual averages.

Table 3 – Design point performance parameters of base case and hybrid cogeneration plants

Parameter	Base Plant	Hybrid Plant
Biomass consumption, kg	13.75	5.30
Boiler steam production, kg/s	50.49	20.23
Solar field steam production, kg/s	-	30.26
Boiler thermal efficiency	0.86	0.91
Solar field optical efficiency	-	0.69
Solar field thermal efficiency	-	0.94

Cycle energy efficiency	0.80	0.89
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Table 4 – Solar field design point parameters

Parameter	
Number of collectors	176
Total net solar field aperture area, m <sup>2</sup>	143868
Incidence angle correction (KIA)	0.98
Peak optical efficiency ( $\eta_{peak}$ )	0.75
Shading loss factor ( $\eta_{shading}$ )	1.00
End loss factor ( $\eta_{endloss}$ )	0.99

As the hybrid plant operates on a fuel-saving strategy in which, at design point, the total steam output is kept equal to the base case, both plants had the same dryer process heat consumption of 25.59 MWth, ethanol production process heat consumption of 83.47 MWth, electricity generation of 30.44 MWe and electricity consumption of 8 MWe.

The annual performance of the base case and hybrid cogeneration plant can be seen in Tab. 5. The calculation of the eucalyptus plantation area required to feed the plants throughout one year was calculated considering a *MIA* of 6874 m<sup>3</sup>km<sup>-2</sup>year<sup>-1</sup> and a biomass density of 485 kg/m<sup>3</sup> (Serenini Jr et al., 2020).

Table 5 – Annual performance parameters of base case and hybrid cogeneration plants

Parameter	Base Plant	Hybrid Plant
Cumulative DNI, kWh/m <sup>2</sup>	-	1929
Biomass consumption, t	433588	380669
Economized fuel, t	-	52919
Solar fraction	-	0.12
Cycle energy efficiency	0.80	0.81
Required eucalyptus plantation area, km <sup>2</sup>	130	114

The annual cumulative energy outputs of the base case and hybrid cogeneration plants are 224178 MWh for the dryer process heat consumption of, ethanol production process heat consumption of 731231 MWh, electricity generation of 266628 MWh and electricity consumption of 70080 MWh.

#### 4. CONCLUSION

The present work aimed to analyze the performance of a CSP/biomass hybrid cogeneration plant used in the corn ethanol industry. The plant was simulated on a typical meteorological year for the city of Barreiras-BA. The results show that, even though the cogeneration plant design used in the corn ethanol industry is already very efficient, the use of the CSP technology as means of generating superheated steam can represent significant reduction of the eucalyptus biomass consumed by the plant without compromising the plants efficiency. This biomass requirement reduction represents a great possibility of increasing earning for the plant however an economic analysis is necessary to evaluate the projects feasibility.

#### 5. ACKNOWLEDGEMENTS

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#### 6. REFERENCES

- Brunet, R., Guillén-Gosálbez, G. and Jiménez, L. (2014), “Minimization of the nonrenewable energy consumption in bioethanol production processes using a solar-assisted steam generation system”, *AIChE Journal*, Vol. 60 No. 2, pp. 500–506.
- Burin, E.K., Buranello, L., Lo Giudice, P., Vogel, T., Görner, K. and Bazzo, E. (2015), “Boosting power output of a sugarcane bagasse cogeneration plant using parabolic trough collectors in a feedwater heating scheme”, *Applied Energy*, Vol. 154, pp. 232–241.
- Cortez, L.A.B., Lora, E.E.S. and Gómez, E.O. (Eds.) (2008), *Biomassa para energia*, Unicamp, Campinas.

- Eckert, C.T., Frigo, E.P., Albrecht, L.P., Albrecht, A.J.P., Christ, D., Santos, W.G., Berkembrock, E. and Egewarth, V.A. (2018), “Maize ethanol production in Brazil: Characteristics and perspectives”, *Renewable and Sustainable Energy Reviews*, Vol. 82, pp. 3907–3912.
- Fuqiang, W., Ziming, C., Jianyu, T., Yuan, Y., Yong, S. and Linhua, L. (2017), “Progress in concentrated solar power technology with parabolic trough collector system: A comprehensive review”, *Renewable and Sustainable Energy Reviews*, Vol. 79, pp. 1314–1328.
- Giglio, A., Lanzini, A., Leone, P., Rodríguez García, M.M. and Zarza Moya, E. (2017), “Direct steam generation in parabolic-trough collectors: A review about the technology and a thermo-economic analysis of a hybrid system”, *Renewable and Sustainable Energy Reviews*, Vol. 74, pp. 453–473.
- International Energy Association (IEA) (2019), *World energy balances: Overview*.
- Kam, M.J. de, Morey, R.V. and Tiffany, D.G. (2009), “Integrating Biomass to Produce Heat and Power at Ethanol Plants”, *Applied Engineering in Agriculture*, Vol. 25, pp. 227–244.
- Karuppiah, R., Peschel, A., Grossmann, I.E., Martín, M., Martinson, W. and Zullo, L. (2008), “Energy optimization for the design of corn-based ethanol plants”, *AIChE Journal*, Vol. 54 No. 6, pp. 1499–1525.
- Mani, S., Sokhansanj, S., Tagore, S. and Turhollow, A.F. (2010), “Techno-economic analysis of using corn stover to supply heat and power to a corn ethanol plant. Part 2: Cost of heat and power generation systems”, *Biomass and Bioenergy*, Vol. 34 No. 3, pp. 356–364.
- Morey, R.V., Tiffany, D.G. and Hatfield, D.L. (2006), “Biomass for Electricity and Process Heat at Ethanol Plants”, *Applied Engineering in Agriculture*, Vol. 22, pp. 723–728.
- Nogueira, A.R., Donke, A.G., Matsuura, M.S.F.I., Matai, P.L.S.H. and Kulay, L. (2014), “Use of Environmental and Thermodynamic Indicators to Assess the Performance of an Integrated Process for Ethanol Production”, *Environment and Natural Resources Research*, Vol. 4 No. 4.
- Renewable Fuels Association (RFA) (2019), *2019 Ethanol Industry Outlook*.
- Serenini Jr. L., Melo, R. R., Stangerlin, D. M., & Pimenta, A. S. (2020). Wood quality of six eucalyptus clones planted in northern Mato Grosso State, Brazil. *Wood Research*, 65(4), 543–554.
- Tiffany, D.G., Morey, R.V. and Kam, M.J. de, 2008. Use of Distillers By-Products and Corn Stover as Fuels for Ethanol Plants. *In Proceedings of Integration of Agricultural and Energy Systems Conference*. Atlanta, USA.
- Wang, L., Hanna, M.A., Weller, C.L. and Jones, D.D., 2009, “Technical and economical analyses of combined heat and power generation from distillers grains and corn stover in ethanol plants”, *Energy Conversion and Management*, Vol. 50 No. 7, pp. 1704–1713.

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