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COMBINED SOLAR-BIOMASS STEAM GENERATION FOR USING IN A POULTRY SLAUGHTERHOUSE SYSTEM

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Abstract. The present work aims to evaluate the thermodynamic and economic feasibility of integrating a Fresnel solar field to produce saturated steam in parallel with a biomass steam generator to supply the heat load demand of a poultry slaughterhouse located in Palotina - PR, Brazil. The biomass steam generator has a nominal capacity of 40 t/h of saturated steam at 9 bar and the Levelized Cost of Heat (LCOH) was calculated as 54.1 R\$/MWh$_t$. The Fresnel solar field was sized to produce 50 % of total steam (20 t/h) at design point condition. In addition, annual simulations were performed to estimate the biomass economy and annual savings due to the hybrid operation. The DNI design point condition was set as 950 W/m^2 corresponding to 21th December solar noon. The thermodynamic and solar models were developed in the Engineering Equation Solver EES $^®$ and Matlab$^®$. The net area of solar field needed was 12.2 hectares, presenting an average annual thermal and optical efficiencies of 46.37 % and 47.6 %, respectively. The hybrid plant showed an efficiency of 82.18 %, producing annually 239.85 GWh$_t$ of thermal energy while LCOH reached 62.8 R\$/MWh$_t$.

Keywords: Thermal energy, Levelized cost of heat, Fresnel field, solar-biomass hybridization, biomass economy.

1. INTRODUCTION

In the last years, attention has been given to the development of alternative technologies to take advantage of renewable energy resources. In this respect, biomass, hydraulic, wind, geothermal, solar and other sources are being explored to provide energy for the economic sectors like industrial, transport, residential, energetic, services and others.

The biomass presents a great potential of growth in the Brazilian market and it is considered as an alternative to diversify the national energy matrix. According EPE (2017) the biomass internal energy supply represented 73.4 Mtep in 2016. Regarding all biomass sources in Brazil, the sugarcane bagasse is the most representative. The sugarcane sector produces about 95% of its own electricity consumption and fully supplies the thermal energy needed in sugar and ethanol production plants (Andrade *et al.*, 2010). The wood corresponds to about 9% of internal energy supply – where 50% of annually processed wood, resulting around of 150 millions/m^3, is exclusively destined for energy purposes (Lopes *et al.*, 2016).

In wherever place of the earth, the solar energy represents a reliable source of energy, once it is clean, free and inexhaustible. Furthermore, solar energy has a great usability potential through systems of capture, storage and energy conversion. Brazil has a great exploitation potential of solar energy due to its favorable climate and geographic location. The global radiation in the horizontal plane ranges between 4500 and 6300 Wh/m^2-day (UFPE & CEPEL/ELETROBRAS, 2000). Besides electricity, the thermosolar energy has the capacity to fulfil a reasonable quantity of thermal energy. Globally, the industrial processes are responsible for 20% of energy consumption, of which almost 60% consists on process heat (Haagan, 2013). In developed economies, solar thermal can provide technically about half of heat process by supplying hot air, cooling, hot water and steam to be used in varies types of industrial processes in temperatures up to 400°C (IRENA, 2015). The thermal energy used at the industry is generally in the form of hot water and saturated steam, usually obtained by burning fuel oil, natural gas and biomass.

This work aims to evaluate the thermodynamic and economic feasibility of integrating a DSG Fresnel solar field to operate in a fuel economy mode in parallel with a typical biomass steam generator system used to feed the steam demand of a poultry slaughterhouse located in Palotina - PR, Brazil. It's a challenge too, to show technic and economic possibilities for implementing the CSP technology in the Brazilian agroindustrial sector.

2. LITERATURE REVIEW

2.1 Fresnel Technology

The Concentrated Solar Power (CSP) Fresnel technology uses a group of flat mirrors to concentrate solar normal irradiation to a fixed linear absorber, in which energy is transferred to a thermal fluid. In case of Fresnel systems, the optical efficiency is lower in comparison with other CSP technologies, nevertheless, the Fresnel modules are more compact requiring less land area and implementation costs are lower. Normally, water is used as the thermal fluid and the steam is directly produced in the linear absorbers. This technology is called as Direct Steam Generator (DSG) and the necessity of intermediary heat exchangers for steam generation is eliminated.

However, the DSG operation has a limitation in terms of solar energy storage. In this regard, the plant hybridization with a conventional biomass steam generator might be the key to ensure continuous operation in all weather conditions. During sunny hours, the steam produced in solar field is used to provide fuel economy and at night or times with no solar radiation incidence, the biomass steam generator load can be recovered to reach the process heat demand.

2.2 Solar-biomass hybridization

The solar radiation and biomass fuel represent a promising alternative for generating thermal energy in the places where they are plentiful. The solar plants have the intermittency of day/night cycle and the periods with reduced radiation like winter and cloudy days. Biomass fueled plants, in the other side, might handle logistic problems and the seasonal availability of biofuels. Based on these limitations, comes up as an alternative the implantation of solar-biomass hybrid power plants which turns possible to maximize the potential of these sources improving the processes efficiency, security of supply, cost reduction and extension of operation hours.

The CSP hybrid plants are commonly installed for power generation. Most cases are related to the integration of solar energy into combined cycles - the so called ISCC power plants. Termosolar Borges built in the north-east of Spain in 2012, is the only case of solar-biomass hybrid plant in operation, which operates with two biomass and an extra natural gas boilers to generate 25 MW of gross capacity (Cot *et al.*, 2010).

The first DSG plant for process heat was constructed in Amman-Jordan, commissioned in mid-2015. This plant supplies saturated steam at 160°C to RAM Pharmaceutical Company for their industrial processes. The project named SolSteam combined a DSG Fresnel solar field with a fossil fuel fired steam generator (Berger *et al.*, 2016).

2.3 Process heat demand and applications

There is more final energy consumption of heat in the industrial sector than electricity is consumed worldwide. The total final energy consumption in 2014 was of 360 EJ and industry sector was responsible of 32 % (115 EJ) - in which 26 % (30 EJ) consisted on electricity and 74 % (85 EJ) on heat (Solar Payback, 2017).

Electricity generation and the residential sector offer a huge potential with respect to the thermosolar applications, however, this source has the potential to satisfy a reasonable quantity of thermal energy demanded in a wide variety of industrial processes. These sectors show two compelling reasons: for one hand the capacity to cover primary energy in final uses totally or partially and for the other hand that the major quantity of heat is in medium and low temperature range, as presented in Table 1.

Table 1. Industries and processes in function of temperatures.

Industry	LOW Below 150 °C	MEDIUM 150 a 400°C
Meat	Washing, sterilizing, cooking	
Preserved food	Pasteurising, sterilizing, cooking, scalding, whitening	
Beverage	Drying, cooking, pasteurizing, sterilizing	
Chemical	Boiling	Distilling
Machinery	Cleaning	Drying
Mining	Cooper electrolytic refining, mineral drying processes	Nitrate melting
Textile	Washing, drying, whitening	Tinging
Wood	Steaming, pickling, cooking	Compression, drying

Source: Solar Payback (2017)

These characteristics make a promising and adequate focus of developing solar fields to heat process. Some of the countries that incorporate solar field in their industries are Chile, Spain, Austria, Germany, Greece, Italy, Jordan, Mexico, India, United States, Egypt and others.

The process fluids conventionally used to attend the thermal necessities of industry are hot water and saturated steam, which are generated by burning fossil fuels, natural gas or biomass. The use of steam present advantages, as: it has high latent heat, is clean and odorless, incombustible, easy to transport and its properties are known. In the case of Brazil, the steam corresponds to 54% of total energy demanded by industry and represents about 20% of national energetic consumption (Silva, 2013).

The application of thermosolar systems in industry is growing, but in a little scale and investment compared with the electricity generation applications. In 2010 it was reported 42 MW_{th} installed capacity in an area of 60,000 m^2 (Vannoni *et al.*, 2008). In 2014, 140 solar field plants which represented more than 136,000 m^2 were supplying process heat with a capacity of 93 MW_{th} (IRENA, 2015). Today, around of 500 unities are installed accumulating an area of 400,000 m^2, generating 280 MW_{th} (Solar Payback, 2017). It is possible to reach a capacity of 850 MW_{th} by 2030, but with a considerable reduction of subsides to fossil fuels and a cost reduction of the CSP technology.

3. SOLAR- BIOMASS HYBRID PLANT MODELLING

In this work a DSG Fresnel solar field is designed to generate saturated steam in parallel with a biomass steam generator. In the solar-biomass hybrid plant is evaluated the performance of combined systems and calculated the annual biomass economy. The C.Vale poultry slaughterhouse is located in Palotina city in the state of Parana, corresponding to the geographic coordinates of 24.28°S- 53.87°O. The solar aided plant layout is presented in Figure 1.
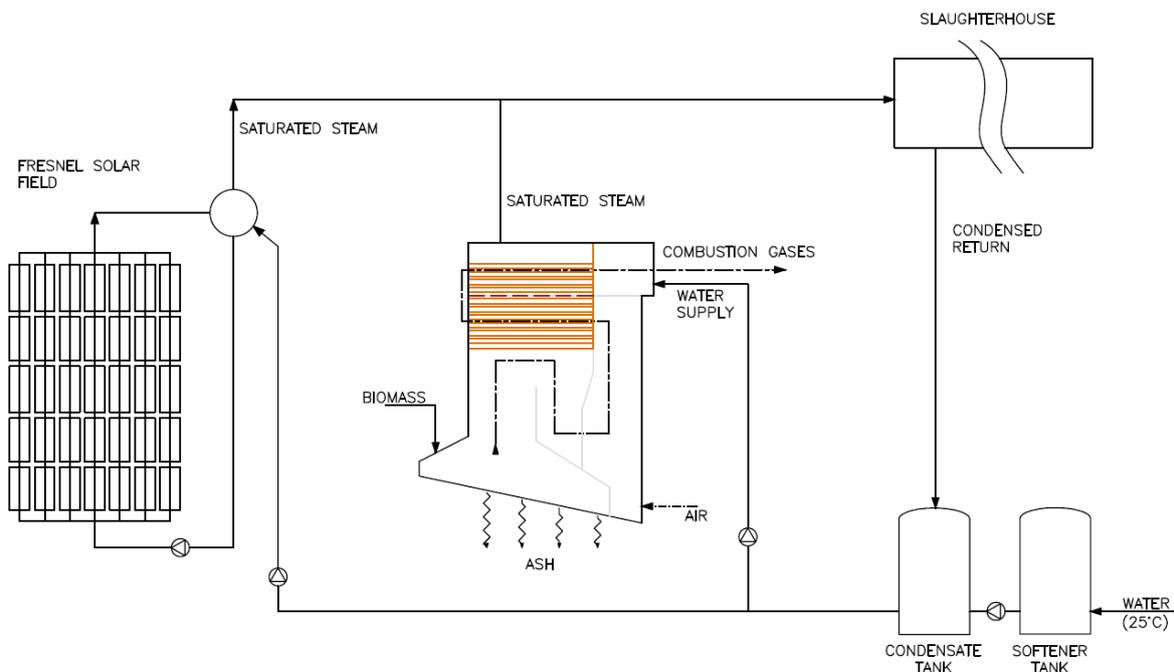

Figure 1. Solar- biomass hybrid plant proposal.

3.1 Thermodinamic modelling

The model is simulated using the computer software Engineering Equation Solver EES®.

The thermodynamic modelling is based on the first law of thermodynamics, mass conservation and on the parameters presented below:

- The steam generator has a nominal steam production capacity of 40 t/h at 9 bar and it burns eucalyptus wood chips with a Lower Heating Value (LHV) of 10366 kJ/kg.
- The minimum load allowable for the steam generator is 45% of its nominal capacity.
- The design point and part load thermal efficiency of biomass steam generator, was indicated by the manufacturer.
- The industry operates during all year with the same charge of steam.

The hourly simulation of the Fresnel solar field is done by using the computer software Matlab® and the adopted assumptions are listed below:

- The Fresnel solar field area was designed to generate 25% of the saturated steam demanded by industry, which was defined as 40 t/h.

- Design point irradiation DNI_{ref}, was equal to 950 W/m^2 at solar noon of 21'st December with an incidence angle of 0.52 degrees.
- The simulation of solar-biomass hybrid system was performed for 8760 hours of one year;
- Simulations were performed by considering the performance data of LF-11 solar collector provided by Industrial Solar (2011)(2011)(2011).

The heat absorbed by the water, which flows in the evacuated tube, $\dot{Q}_{abs}$ [W], was simulated according to a steady-state model represented by Eq. (1) and Eq. (1),

$$\dot{Q}_{abs}=A_{cs}\cdot[DNI\cdot\eta_{opt}-q''_{loss}] \tag{1}$$

$$\eta_{opt}=\eta_o \cdot IAM_L \cdot IAM_T \cdot F_{sm} \tag{2}$$

where A_{cs} [m^2] is the net aperture area of primary reflectors, DNI [W/m^2] is the direct normal irradiation, η_{opt} is the optical efficiency, q''_{loss} [W/m^2] represents the thermal losses. η_o=0,635 is the optical efficiency for sun in zenith corrected due to astigmatism and shading by receiver, IAM$_L$ and IAM$_T$ are the Longitudinal and Transversal Incidence Angle Modifiers, respectively. These IAM take into account shading, blocking and cosine losses and they are a function of incidence θ_i and transversal θ_t angles. The parameter F_{sm}=0,95 is the soiling mirror factor which has high influence on the optical performance of Fresnel modules.

The solar field thermal losses q''_{loss}[W/m^2] are calculated per square meter of aperture area according Eq. (3).

$$q''_{loss}=q''_{lossABS}+ q''_{lossP} \tag{3}$$

The absorber tubes heat losses $q''_{lossABS}$ [W/m^2] is calculated with Eq. (4), while the header pipes heat loss is calculated by the empirical correlation proposed by Patnode (2006) (Eq. (5)),

$$q''_{lossABS}=\mu_l\cdot\Delta T^2 \quad ; \quad \Delta T=\frac{(T_{out}+T_{in})}{2}-T_{amb} \tag{4}$$

$$q''_{lossP} = 0,01963\cdot\Delta T - 1,683\text{E-4}\cdot\Delta T^2 + 6,78\text{E-7}\cdot\Delta T^3 \tag{5}$$

where μ_l=0,00043 [W/m^{2}K^2] is the energy loss coefficient and ΔT [C] is the difference between the average heat transfer fluid temperature in solar field receivers and the ambient temperature.

4. ANNUAL PERFORMANCE INDEXES

The solar field annual optical efficiency is defined as the ratio between the energy reflected by primary mirrors to the absorbers and the total energy incident at primary mirrors, as indicated by Eq. (6). The annual thermal efficiency is calculated as the ratio between the absorbed energy and the total energy incident in the primary mirrors, Eq. (7).

$$\eta_{OPT}=\sum_{i=1}^{8760}\frac{DNI_{(i)} \cdot \eta_{opt\,(i)}}{DNI_{(i)}} \tag{6}$$

$$\eta_{TH}=\sum_{i=1}^{8760}\frac{\dot{Q}_{abs\,(i)}}{DNI_{(i)} \cdot A_c} \tag{7}$$

According to Srinivas et al. (2014) the annual hybrid efficiency was defined as the total useful energy obtained divided by the sum of the available energy from solar and biomass sources, as indicated by Eq. (8),

$$\eta_{HYB}=\sum_{i=1}^{8760}\frac{\dot{Q}_{TOTAL(i)}}{\dot{m}_{cb(i)}\cdot LHV+DNI_{(i)}\cdot A_c} \tag{8}$$

where $\dot{m}_{cb}$ [kg/s] is the mass flow rate of biomass.

The cost of delivered heat produced by base case and hybrid plants was evaluated by using the Levelized Cost of Heat (LCOH) parameter. The LCOH consists on an economic assessment that includes all costs over the life time of plant:

initial investment, operation and maintenance costs, cost of fuel, cost of capital (Gabbrielli *et al.*, 2014), as indicated by Eq. (9),

$$LCOH = \frac{(CC + CT) \cdot \left(\frac{i \cdot (1 + i)^n}{(1 + i)^n - 1} \right) + O\&M}{Eth} \tag{9}$$

where *CC* [R\$], *CT* [R\$] and *O&M* [R\$/year] are the capital cost, land cost and operation and maintenance cost, respectively. *Eth* [MWh/year] is the energy output during a year, *i* [%] is the interest rate and *n* the life time in years. The parameters used for the economic in this works analysis are presented at Table 2.

Table 2. Parameters used for economic analysis.

Parameter	Unit	Value
Steam generator[*]	R\$	12×10^6
Employee charge[*]	R\$/year	432,000
Biomass[*]	R\$/t	120
Solar field investment[*]	R\$/kWt	2063
Land investment[*]	R\$/m^2	11
O&M	-	2% of CC
Interest rate, *i*	-	8%
Life time of plant, *n*	Years	25

[*] Quoted cost.

5. RESULTS AND DISCUSSIONS

The main results related to base case plant simulation are presented in Table 3. When the steam generator produces, a rate of 40 t/h of saturated steam at 9 bar, the thermal efficiency presented is 87.6 %, with a biomass consumption of 10.85 t/h and 95,046 tons per year. The LCOH for the steam generation base case was 54.1 R\$/MWh$_t$ it is reasonable value, thanks to the efficiency of steam generator and consequently the accumulated energy produced from a local cheap fuel.

Table 3. Base case steam generation performance.

Parameter	Unit	Value
Steam rate	t/h	40
Biomass consumption	t/h	10.85
Steam generator efficiency	%	87.60
Thermal power	MW$_t$	27.37
Accumulated biomass consumption	t/year	95,046
Thermal energy produced	MWh$_t$/year	239,726.2
Levelized cost of heat, LCOH	R\$/MWh$_t$	54.1

As it was previously defined, the solar field was designed to attend 10 t/h of saturated steam at design point condition to displace the biomass consumption during sunny hours. The solar field capacity was calculated based on design point parameters and presented optical and thermal efficiencies of 60% and 58.9%, respectively. The land area required for solar field installation was determined by considering the mirrors to land area factor of 0.67 indicated by manufacturer. The solar field performance results, at design point, are presented in Table 4.

Table 4. Fresnel solar field performance at design point.

Parameter	Unit	Value
Thermal power	MW$_t$	6.84
Thermal efficiency	%	60
Optical efficiency	%	58.9
Primary mirrors net area	ha	12.2
Land area	ha	18.3

Table 5 presents annual performance and economic results reached with the solar field. The local year-round accumulated DNI was equal to 1612.72 kWh/m^2.year, what is a value relatively low compared to regions where CSP are installed. In function of thermal efficiency and losses, the solar heat delivered by solar field during a year was of 9065.7 MWh$_t$/year. The solar field thermal and optical annual efficiencies were of 46.37 % and 47.6 %, respectively. The investment needed for solar field is around of 14.3 millions, which is very high due to almost all components of CSP technology should be imported. However, the land investment for an area of 18.3 hectares in Palotina city is on 201,300 R$, very lower when compared to the solar field costs. The biomass saved in the year was of 3579 tons that represent an economy 429,436 R$. The LCOH of steam produced by solar field was 163.8 R$/MWh$_t$, which is 3.3 times that the obtained of base case.

Table 5. Annual performance and economic results on solar field.

Parameter	Unit	Value
Accumulated DNI	kWh/m^2.year	1612.72
Thermal energy produced	MWh$_t$/year	9065.7
Solar field thermal efficiency η_{TH}	%	46.37
Solar field optical efficiency η_{OPT}	%	47.6
Solar field investment	R$	14.3x10^6
Land investment	R$	201,300
Biomass economy	t/year	3579
Money economy in biomass	R$/year	429,436
Levelized cost of heat, LCOH	R$/MWh$_t$	163.8

The hybrid concept annual simulation was done in order to incorporate the Fresnel solar field to work in parallel with the steam generator. The main results related to the hybrid plant performance are showed in Table 6. The total thermal energy produced by the hybrid plant was equal to 230.78 GWh$_t$. The hybrid efficiency presented was 82.18% and a LCOH of 62.8 R$/MWh$_t$ which is 10 % more expensive than the base case value.

Table 6. Hybrid plant annual performance.

Parameter	Unit	Value
Total thermal energy produced	GWh$_t$/year	239.85
Hybrid efficiency η_{HYB}	%	82.18
Levelized cost of heat, LCOH	R/MWh_t$	62.8

A typical day of solar field operation is presented at Figure 2. Note that the difference between the DNI incident heat and the specific useful heat delivered by the solar field is due to its thermal efficiency.
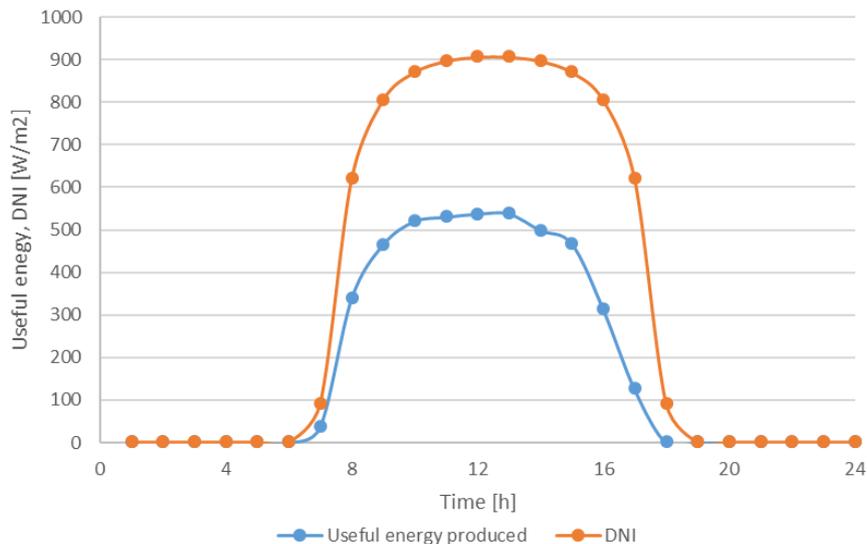

Figure 2. A day of solar field operation

6. CONCLUSIONS

Biomass is a renewable energy source widely explored in Brazil which represents 25.5% of internal energy supply. Specifically, in case of food industry in the south of Brazil, wood represents the most used biomass source of fuel for steam production. In the specific case of the biomass plant evaluated in this work, the low cost of wood reflected on the low LCOH of 54.1 R$/MWht on delivered heat.

A Linear Fresnel solar field was considered in this work as an alternative for generating saturated steam for the evaluated industrial meet processing unit. The Fresnel CSP technology turns possible to generate steam directly in the absorber tubes, avoiding the necessity of expensive investments in heat exchanger sets and storage systems. The DSG system is considered one of the best CSP options for process steam generation to provide the heat demand of industrial processes once it presents a simpler configuration plant resulting in reduced capital, operation and maintenance costs.

In developed economies, the Fresnel and other CSP technologies present competitive costs due to their industry develop and construct them and because the scarcity of other alternative energy sources, create the necessity to make available these systems to the society with affordable investment and government incentives. However, in South America, has others kinds of alternative cheaper sources to make expensive that news that are maturing. This is reflected in the solar LCOH of 163.8 R$/MWht.

The optical and thermal efficiency of solar field are relatively low, compared with others CSP technologies, whence the energy produced and biomass economized are low compared with the investment needed.

Although in one hand the Fresnel system is actually expensive, on the other hand when it is incorporated with a conventional biomass steam generator, in a hybrid approach, both sources are complemented and the resulting combined LCOH is reduced. In case of this work, a combined LCOH of 62.8 R$/MWht was estimated in case of hybrid operation.

7. ACKNOWLEDGEMENTS

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9. RESPONSIBILITY NOTICE