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THERMODYNAMIC AND ECONOMIC ANALYSIS OF A BIOMASS POWER PLANT AIDED BY LINEAR FRESNEL COLLECTORS

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Abstract. *The present study aims to evaluate the integration of a Linear Fresnel solar field in a feedwater heating scheme with a biomass power plant located in Campo Grande – MS, Brazil. It was performed a thermodynamic simulation of 12 MW regenerative Rankine cycle. The solar field was integrated into the original plant providing the feedwater heating steam extraction displacement. The solar field area was dimensioned for a solar multiple equal one (MS=1) according to the selected design point. The feedwater at 8.83 MPa was directly heated through the Linear Fresnel collectors from 195 to 220°C. After the simulation for a typical meteorological year it was observed the additional energy generation of 662,898 kWh due to the solar integration, that corresponded to 0.63% more when compared to the biomass base case. This also represented supplying around 350 additional typical Brazilian homes with solar electricity. Finally, the solar to electricity annual efficiency of the solar plant was equal 14.5%, that is above to the obtained by the typical dedicated Linear Fresnel power plants. This led to the Levelized Cost of Energy (LCOE) improvement.*

Keywords: *Linear Fresnel, solar energy, biomass, boiler feedwater heating, levelized cost of electricity.*

1. INTRODUCTION

In 2013 the biomass installed capacity reached 10,768 MW, that represents 8.09% of the Brazilian electricity matrix, including imports. In the total amount of the biomass capacity, the sugarcane bagasse corresponds to the main share (BIG/ANEEL, 2013). One problem related to the biomass power plants operation, however, consists on the availability and quality of the fuel resources along the year, that can lead to the capacity factor minimization. In this context, studies have been made with the objective to investigate the integration of solar thermal fields with conventional Rankine plants in order to minimize the disadvantages of the dedicated units, to reduce fuel consumption, improve the thermodynamic generation efficiency and, as a consequence, to produce cheaper energy (Häberle, *et al*. 2002).

The parabolic trough is predominant in concentrating solar power (CSP) for electricity generation. However, other CSP technologies recently have become competitive, as the Linear Fresnel. A Linear Fresnel collector uses flat mirrors to redirect solar normal irradiation to a fixed receptor above the mirrors. The receptor contains water as the operation fluid, that absorbs the reflected energy as heat. This technology is characterized by a lower optical efficiency in comparison to other CSP technologies. Nevertheless, the Fresnel modules are more compact, requiring less land area and, therefore, providing more competitive costs.

The present study aims to evaluate the thermodynamic and economic benefits of integrating a Linear Fresnel solar field in a feedwater heating scheme with a hypothetical biomass regenerative Rankine power plant simulated in the city of Campo Grande – MS, Brazil.

2. SOLAR AIDED POWER PLANT

2.1 Power plant and integration description

A hypothetical 12 MW capacity biomass fueled Rankine cycle was considered for the present study. The configuration and operational parameters of the biomass power plant are based on the data presented by Hou, *et al*. (2010), as shown in Fig. 1, consisting of a condensation steam turbine with five extractions for heating the feedwater.

In order to integrate the solar energy for preheating the feedwater five alternatives are possible to be considered regarding steam extraction replacement for solar energy. The higher the exergy of the displaced steam extraction, the better the efficiency and economy. So it seems reasonable that the first extraction is the best alternative for integration and therefore it was selected to be evaluated.

For integration, a diverter valve is considered located at the point where the feedwater stream has 195°C and 88 bar before the higher temperature heater. At this point, the feedwater was simulated as partially diverted to the Linear Fresnel solar field according to local irradiation. The diverted stream was heated up to 220°C and reintroduced into the cycle. As the turbine extraction was displaced by the solar thermal load, the main steam flow rate was held unchanged to increment energy production (power boost mode operation).

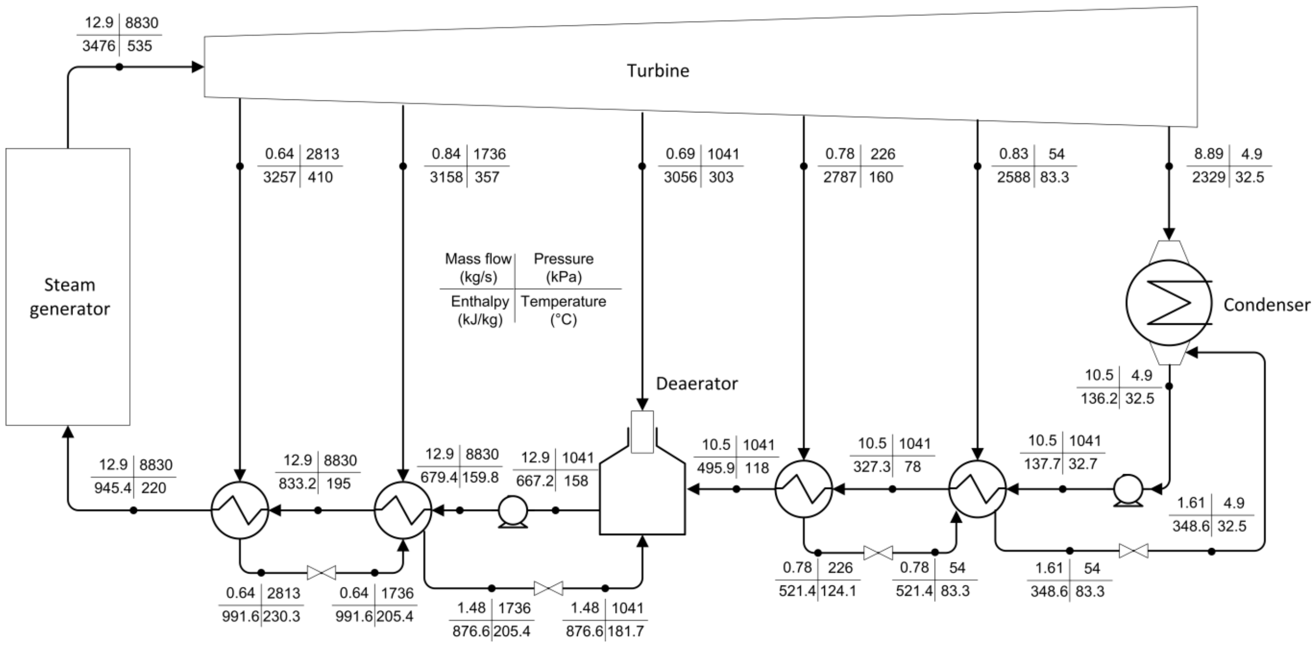

Figure 1 – Illustration of the simulated regenerative Rankine cycle – Adapted from Hou, et al., (2010)

2.2 Thermodynamic modelling

The biomass cycle thermodynamic modeling was performed using Equation Engineering Solver (EES) software considering the mass and energy conservation equations at steady-state operation. The isentropic efficiency for pumps and turbine were considered equal to 80% and thermal efficiency of the steam generator was considered equal to 85%. Pressure drop at condenser, boiler and pipes was neglected, as well as heat losses in pipes.

The solar field was simulated using technical specifications of solar collectors NOVA-1 developed by Novatec Solar (Novatec Solar, 2009). The governing equation to obtain the solar energy absorbed by feedwater, $\dot{Q}''_{abs}$ [W/m²], is

$$\dot{Q}''_{abs} = DNI\ \eta_{opt} - P_{loss} \tag{1}$$

where DNI [W/m²] is the direct normal irradiation, η_{opt} is the optical efficiency of modules and P_{loss} [W/m²] is the thermal losses due to temperature difference to the ambient. The term η_{opt} is given by Eq. 2, wherein $\eta_{opt\_max} = 0.68$ and the transversal and longitudinal incidence angle modifier parameters, K_t and K_l, are represented in Fig. 2. Finally, the term P_{loss} is given by Eq. 3, for the empirical parameters u_o and u_1 equal to 0.056 [W/m².K] and 0.000213 [W/m².K²], respectively. The mean feedwater temperature difference to the ambient is given by Eq. 4.

$$\eta_{opt} = \eta_{opt\_max} \cdot K_t \cdot K_l \tag{2}$$

$$P_{loss} = u_o \cdot \Delta T + u_1 \cdot \Delta T^2 \tag{3}$$

$$\Delta T = \frac{(T_{in} + T_{out})}{2} - T_{amb} \tag{4}$$

The available heat delivered by solar field $\dot{Q}_{av}$ [W] was determined by Eq. 5, where A_{sf} [m²] is the total aperture area of the solar field.

$$\dot{Q}_{av} = A_{sf}\ \dot{Q}''_{abs} \tag{5}$$

The simulation of solar collectors was performed for a typical meteorological year data (TMY data), set for the city of Campo Grande (-54.667°, -20.467°), using the computer software Matlab and considering the following assumptions:

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- Design point irradiation, DNI_{ref} equal to 855 W/m^2 at solar noon on 25'th December (longitudinal incidence angle of 3.5 degrees);
- Solar field orientation at north-south;
- Pressure drop of operation fluid at solar field neglected;
- Multiple solar equal to 1.

Design point is typically adopted in the summer solstice for the respective hemisphere, in this case on December 21. Direct normal irradiation at noon of this day was lower than expected and thus could cause a sizing field larger than desired. Accordingly, it was adopted the data from December 25 at noon which obtained regular values. The solar field was sized to displace total steam turbine extraction at the design point irradiation. In order to achieve this condition it was proposed the installation of 2568 m^2 aperture area NOVA-1 concentrators in a land area of 3300 m^2. The layout of solar field consisted of 5 solar modules arranged in series. The integration was simulated considering one hour time steps.

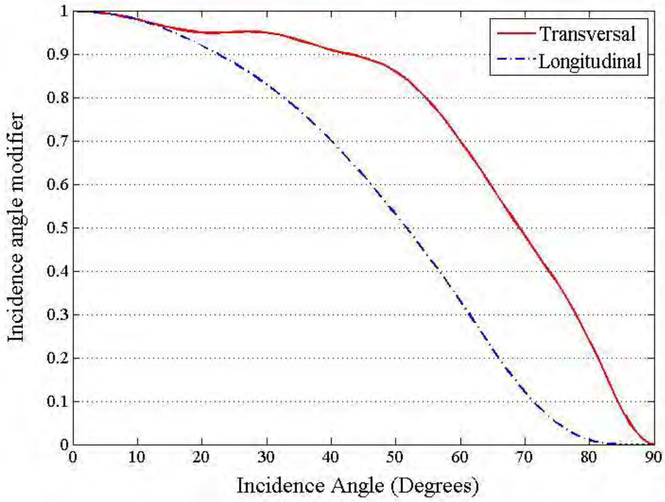

Figure 2 – Incidence angle modifier parameters

2.3 Thermodynamic annual performance indexes

Thermodynamic annual performance indexes were defined to evaluate the solar integration. The annual solar-to-electricity efficiency was defined as the total additional work produced due to solar field integration divided by the total solar energy incident in the solar field (Eq. 6). The solar field efficiency was defined as the reason of total thermal energy absorbed by the feedwater and the total solar energy incident in the collectors (Eq. 7). Finally, thermodynamic cycle conversion efficiency was given by the ratio of total extra work generated over one year and the thermal energy absorbed by feedwater (Eq. 8).

$$\eta_{se} = 100 \cdot \sum \frac{W_{extra}}{DNI \cdot A_{sf}} \quad (6)$$

$$\eta_{sf} = 100 \cdot \sum \frac{\dot{Q}_{av}}{DNI \cdot A_{sf}} \quad (7)$$

$$\eta_{ct} = 100 \cdot \sum \frac{W_{extra}}{\dot{Q}_{av}} \quad (8)$$

2.4 Levelized cost of electricity

The levelized cost of electricity was evaluated according to the EGC spreadsheet model (IEA, 2005). The methodology aims to ensure the comparison between technologies through the associated costs, eliminating governmental exemptions and subsidies. In addition, the costs involved in the calculation are limited to power generation, so does not include grid costs. The method assumes that the cost per MWh is constant throughout the life of the plant. Thus, matching costs with generated revenues (Eq. 9),

$$LCOE = \frac{\left(\Sigma_{Period}\frac{Costs}{(1+r)^t}\right)}{\left(\Sigma_{Period}\frac{Generated\ energy}{(1+r)^t}\right)} \quad (9)$$

where LCOE is the levelized cost of electricity, r is the discount rate and t is the respectively year in the sum.

A sensitivity analysis reported by IEA (2005), showed that the main factors in calculating the LCOE for solar generation technology are the load factor, discount rate, construction costs and lifetime. Among these, the only variable not defined in this study is the construction cost, since other factors are predetermined by the methodology or are consequences of the simulation. Accordingly, the calculation of the construction costs was performed with greater attention.

A survey was conducted to search reliable sources to estimate the initial investment, construction costs and costs of operation and maintenance. The initial investment was assessed by importing Fresnel collectors, according to the respective Mercosul Common Nomenclature (NCM) to obtain the value of the nationalized product.

The discount rate is a term with high influence on the result of the LCOE, however the methodology standardizes at 5% and 10%. This term represents the cost of capital and the risks involved in investment due to the absence of a specific risk to the market in question, that is usually based on market interest rates or weighted average cost of capital (WACC). The discount rate also does not include inflation variations.

3. RESULTS AND DISCUSSIONS

3.1 Thermodynamic results

The solar field thermal load was able to decrease the higher temperature steam extraction as DNI was available. This condition allowed extra work generation. The additional plant output after the typical meteorological year simulation was equal to 662,898 kWh/year. This energy would be able to supply about 350 typical Brazilian homes - data obtained through the Brazilian average residential consumption (ANEEL, 2013).

The results related to the thermodynamic solar integration efficiencies are presented at Tab. 1. The conversion efficiency of solar irradiation into electricity was high when compared to the efficiencies typically obtained in dedicated Fresnel plants, 9-12% (Téllez, 2011). This was due to the low solar field mean temperature operation related to the feedwater heating, that minimizes the heat losses to the ambient. Furthermore, the avoided steam extraction mass flow displaced has high exergy level, increasing the electricity generation.

Table 1 – Integration annual efficiencies

Thermodynamic annual performance indexes	Value
Solar-to-electricity efficiency (η_{se})	14.5 %
Solar field efficiency (η_{sf})	44.5%
Cycle conversion efficiency (η_{ct})	32.5%

Randomly selected operation days are presented in Fig. 3, showing the DNI, the absorbed heat by feedwater ($\dot{Q}''_{abs}$) and additional work. The difference between DNI and $\dot{Q}''_{abs}$ is due to the thermal efficiency of solar field. Finally, it is also represented the instantaneously additional power generation at the steam turbine each hour of simulation.

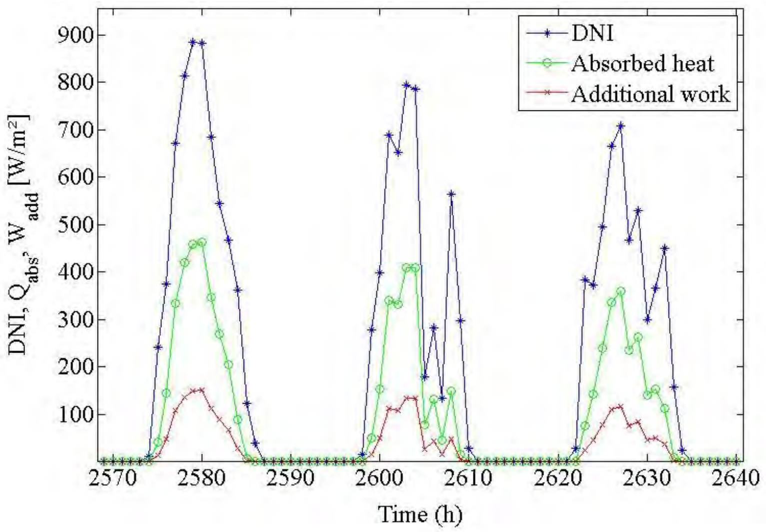

Figure 3 - Direct normal irradiation over absorbed heat

3.2 Economic results

The calculation of the various costs involved in measuring the levelized cost of electricity is somewhat difficult to evaluate due to few data available in the literature. A strategy of assessing optimist and pessimist scenarios was adopted for the project of implementing a Linear Fresnel solar field integration in a biomass plant. The results obtained in this step are shown in Tab. 2.

Table 2 – Economic results for optimist and pessimist scenarios

		Optimist	Pessimist
Net annual electric energy production (kWh/y)		662,898	662,898
Load factor (%)		16.3	16.3
Expected lifetime (years)		25	25
Specific collector invest (US$/m²)		172	257
Land costs (US$)		8,500	13,000
Field investment (US$)		441,696	659,976
Annual O&M costs		9,000	10,000
Estimated LCOE (US$/MWh)	Discount rate of 5%	100	150
	Discount rate of 10%	140	210

One of the main advantages of Linear Fresnel technology is its compactness. Nevertheless, notice that land costs represented a low investment when compared to the solar field costs. This is due to the considerable offer of land in the Campo Grande region considered for simulation. In this sense, a higher efficiency solar collector technology, such as parabolic trough, needs to be evaluated as the required mirror area is the factor that prevailed in LCOE.

Considering the calculated LCOE, it had competitive values when compared with average global prices of 200 US$/MWh (OpenEI, 2012), which is almost equal to the most pessimist scenario obtained in this work. This is mainly due to the high solar-to-electricity efficiency obtained in the simulated integration.

4. CONCLUSIONS

A Linear Fresnel solar field was considered in this work as a reliable alternative for feedwater heating of a biomass power plant located in Campo Grande, performing a thermodynamic simulation of a 12 MW regenerative Rankine cycle. The solar field was integrated into the original plant replacing the higher pressure steam extraction for solar energy. The main conclusions are presented in the following:

- It was possible to increase the power output of plant, contributing to minimization of the problem related to biomass seasonality;
- A high solar-to-electricity efficiency was obtained for the proposed configuration due to the low feedwater mean temperature and high exergy steam displacement;
- Levelized cost of energy obtained was, in the pessimist scenario, almost equal to the average of concentrating solar power technologies.

Further integration layouts are planned to be studied in order to improve the solar share. Also, a more detailed model should be performed to investigate the influence of the solar field integration on the operation of steam generator and turbine due to variations on mass flow. Finally, the parabolic trough integration is also planned to be evaluated as it has higher optical efficiency when compared to the Linear Fresnel technology, despite its worst land usage factor.

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