27th ABCM International Congress of Mechanical Engineering
December 04-08, 2023, Florianópolis-SC, Brazil

COB-2023-0744
ANALYSIS OF A SOLAR/BIOMASS HYBRID POWER PLANT IN PARAÍBA CITIES, BRAZIL

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Abstract. *The utilization of fossil fuels has propelled the development of societies in industrial and urban contexts throughout history. However, their combustion leads to significant socio-environmental impacts, highlighting the need for a transition to low-emission renewable energy sources. A promising alternative is the hybridization of solar energy and biomass, combining the performance of solar thermal energy during periods of high direct solar radiation with the intervention capacity of biomass during periods of lower yield. This study aims to evaluate the thermodynamic parameters of a solar/biomass hybrid power plant located in Brazil, specifically in three cities in Paraíba: João Pessoa, Coremas, and Santa Luzia. The objectives are to determine which of these locations offers the best overall efficiency for such a hybrid facility. Engineering Equation Solver (EES) computational software performed the thermodynamic equations, and System Advisor Model (SAM) was used to assess the solar characteristics of each region, such as the Direct Normal Irradiation (DNI) parameter. The Coremas City presented the best hybrid plant efficiency. This research will foster further studies on the concentrated solar power system in the context of electricity generation in Brazil, thereby delineating a promising outlook for scientific progress in this field.*

Keywords: *biomass, concentrated solar power, hybrid plant, renewable energy, solar energy.*

1. INTRODUCTION

Fossil fuels, such as coal, oil, and natural gas, have been widely used in energy generation due to their abundant availability, accessibility, and ability to continuously meet energy demands. However, the combustion of these fuels raises concerns related to climate change and environmental impacts due to greenhouse gas emissions, such as carbon dioxide (CO_2). This has driven global interest in transitioning to clean and sustainable energy sources (ANVARI et al. 2018).

Regarding energy generation systems, the innovative approach of hybrid generation, which combines solar and biomass energy, stands out, offering benefits such as a continuous supply of electricity, even during nighttime or low-light conditions. This is possible because the inherent intermittency of solar generation can be compensated for by the constant availability of energy from biomass. Furthermore, this approach optimizes local natural resources and contributes to the reduction of greenhouse gas emissions (SURESH et al., 2019).

To analyze the thermodynamic parameters of a hybrid power plant with an integrated water/steam, air, and gas cycle, combining solar energy and biomass from sugarcane bagasse, operating on the principle of a simplified regenerative vapor Rankine cycle, three cities in the state of Paraíba, Brazil will be considered: João Pessoa, Coremas, and Santa Luzia. The focus is on identifying the region with the highest overall efficiency, through various combinations of evaporation pressure and turbine inlet temperatures, enabled by specialized software such as EES for thermodynamic equation resolution and SAM for assessing specific solar characteristics of each region, considering the parameter known as Direct Normal Irradiance (DNI).

2. MATERIAL AND METHOD

2.1 Cycle Studied

The case study of this research consists in implanting a solar/biomass hybrid plant in the state of Paraíba. In this scenario, parabolic solar collectors are used as they are the most widely used model for high-temperature collectors. As for biomass, the energy generation from sugarcane bagasse is chosen due to the extensive sugarcane plantation established in the analyzed state. The cycle is based on the studies by Srinivas and Reddy (2014) but adapted to the state of Paraíba and utilizes sugarcane bagasse biomass.

The cycle of the hybrid plant depicted in Figure 1 consists of a water/steam, air, and gas circuit operating in a simple regenerative Rankine steam cycle. Therefore, the operating principle involves the combustion of biomass, resulting in hot gases that heat the feedwater and generate superheated steam. The superheated steam converts thermal energy into mechanical energy in the turbine, which, coupled to the generator, converts mechanical energy into electrical energy. Subsequently, through the condenser, pumps, deaerator, and valve, the fluid is able to return to the boiler and the solar collectors, thus completing the cycle (Çengel and Boles, 2013).

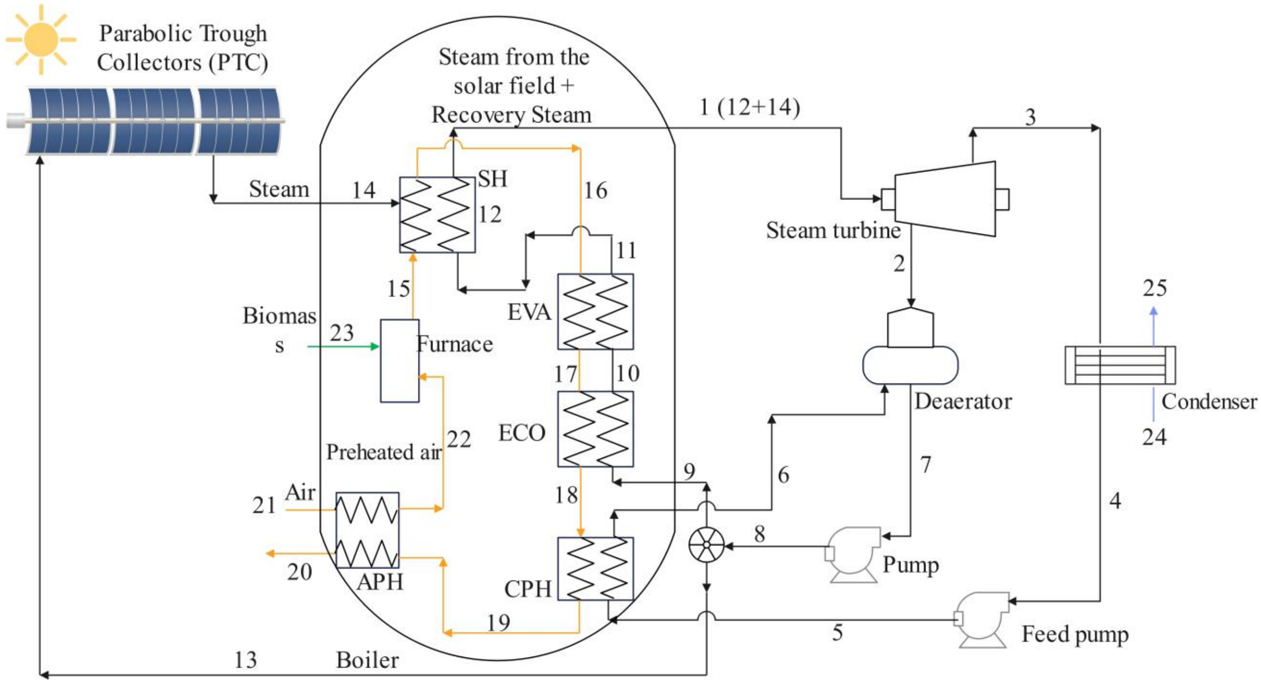

Figure 1. Diagram of the solar/biomass hybrid plant (Adapted from Srinivas and Reddy, 2014).

The proposal of the hybrid plant is to generate steam from both sources during the day, while steam is only generated from biomass at night. Biomass plant is designed to operate under partial load and full load conditions. The partial load condition occurs during the daytime when the biomass plant operates alongside the solar plant. The plant's proposal involves reducing the contribution of biomass during the day and gradually increasing the operation of the solar plant so that both plants operate at half-load around noon. On the other hand, the plant requires biomass generation to operate at full load during the nighttime due to the lack of energy utilization from the solar plant during this shift (Srinivas and Reddy, 2014).

2.2 Energy analysis of the studied cycle

The power calculations for the solar/biomass hybrid plant are performed using the EES software due to its simplicity in solving thermodynamic stages and its library containing various thermodynamic properties. According to Srinivas and Reddy (2014), the isentropic efficiency of the turbine and pump is 75%, and the generator efficiency is 98%. The cycle modeling is obtained based on the principle of mass conservation and the first law of thermodynamics.

2.2.1 Turbine

From the principle of mass conservation in the turbine, Equation 1 is obtained.

$$\dot{m}_1 = \dot{m}_2 + \dot{m}_3 \tag{1}$$

Where:
$\dot{m}_1$ is the mass flow rate entering the turbine,
$\dot{m}_2$ is the mass flow rate exiting the turbine to the deaerator,
$\dot{m}_3$ is the mass flow rate exiting the turbine to the condenser.

In turbines, there is an efficiency known as isentropic efficiency, which is the ratio of the actual work output of the turbine to the isentropic work, in other words, the ideal work if the inlet state and pressure were to maintain constant entropy. Thus, Equation 2 determines the isentropic efficiency of the turbine.

$$\eta_{ise,t} = \frac{h_1 - h_2}{h_1 - h_{2s}} \tag{2}$$

Where:
$\eta_{ise,t}$ is the isentropic efficiency of the turbine, which in this case is 75%,
h_1 is the enthalpy of the fluid in the superheated vapor state at the turbine inlet,
h_2 is the enthalpy of the fluid in the saturated vapor state at the turbine outlet,
h_{2s} is the isentropic enthalpy of the fluid in the saturated vapor state at the turbine outlet.

The power generated by the turbine is obtained through Equation 3.

$$\dot{W}_t = \dot{m}_1 \left((h_1 - h_2) + (1-y).(h_2 - h_3)\right) \tag{3}$$

Where:
h_3 is the enthalpy of the fluid in the mixed state at the turbine outlet,
y is the mass fraction of vapor extracted from the turbine (m_2/m_1).

2.2.2 Condenser

The condensers are devices that serve to condense the fluid and are located at the turbine outlet. Equation 4 quantitatively highlights the heat rejected from the cycle.

$$\dot{Q}_{cond} = \dot{Q}_{out} = \dot{m}_3 \, .(h_3 - h_4) \tag{4}$$

Where: h_4 is the enthalpy of the saturated liquid leaving the condenser.

2.2.3 Pumps

Just like turbines, pumps also use the concept of isentropic efficiency, which represents the ratio between the isentropic work (ideal) and the actual work of the pump. Therefore, considering the isentropic efficiency of the pumps, Equation 5 is established for the pump and Equation 6 is established for the feed pump.

$$\eta_{ise,fp} = \frac{h_{5s} - h_4}{h_5 - h_4} \tag{5}$$

Where:
$\eta_{ise,fp}$ is the isentropic efficiency of the feed pump, which in this case is 75%,
h_{5_s} is the isentropic enthalpy of the fluid in the compressed liquid state at the outlet of the feed pump,
h_4 is the enthalpy of the fluid in the saturated liquid state at the condenser outlet,
h_5 is the enthalpy of the fluid in the compressed liquid state at the outlet of the feed pump.

$$\eta_{ise,p} = \frac{h_{8_s} - h_7}{h_8 - h_7} \tag{6}$$

Where:
$\eta_{ise,p}$ represents the isentropic efficiency of the feed pump, which in this case is 75%,
h_{8_s} is the isentropic enthalpy of the fluid in the compressed liquid state at the outlet of the pump,
h_7 is the enthalpy of the fluid in the saturated liquid state at the outlet of the deaerator,
h_8 is the enthalpy of the fluid in the compressed liquid state at the outlet of the pump.

2.2.4 Deaerator

The deaerator's contribution constitutes the feed fluid heating system. By applying the control volume boundary, it is possible to develop Equations 7, 8, and 9.

$$\dot{m}_7 = \dot{m}_2 + \dot{m}_6 \tag{7}$$

$$\dot{m}_7 h_7 = \dot{m}_2 h_2 + \dot{m}_6 h_6 \tag{8}$$

$$1h_7 = yh_2 + (1-y)h_6 \tag{9}$$

2.3 Equation of cycle efficiencies

The thermodynamic analysis of the model established in the case study is performed based on the mass balance equations, energy balance equations, second law balance equations, and state equations provided by Srinivas & Reddy (2014). Therefore, to determine the proportion of solar energy sharing, the SESR (Solar Energy Sharing Ratio) parameter is used.

$$SESR = \frac{Use\ of\ solar\ energy}{Use\ of\ solar\ energy\ x\ Use\ of\ biomass\ energy} \tag{10}$$

$$SESR = \frac{m_{13}(h_{14}-h_{13})}{[m_{13}(h_{14}-h_{13})] + [m_5(h_6-h_5) + (1-m_{13})(h_1-h_9) + m_{13}(h_{14}-h_{13})]} \tag{11}$$

By simplifying the expressions, the generation of steam from solar energy (m_{13}) is defined in such a way that for this thermodynamic analysis, SESR is a constant of 0.5, representing a 50% heat acquisition from solar collectors during the peak solar incidence, with the remaining heat being obtained from biomass. Therefore, the water feeding to the solar collectors per unit mass of steam at the turbine inlet is given by:

$$m_{13} = \frac{SESR\big(m_5(h_6-h_5) + (h_1-h_9)\big)}{h_{14}-h_{13} + SESR(h_{13}-h_9)} \tag{12}$$

The heat from the solar collector is given by:

$$q_{solar} = \eta_{collector,b} I_b A_{total,c} \tag{13}$$

The water feeding to the solar collectors per unit mass of steam can be summarized as:

$$m_{13} = \frac{q_{solar}}{h_{14}-h_{13}} \tag{14}$$

The feedwater to the biomass boilers is:

$$m_9 = m_8 - m_{13} \tag{15}$$

The supply of heat from biomass energy is:

$$q_{biomass} = m_5(h_6-h_5) + m_9(h_1-h_9) + m_{14}(h_1-h_{14}) \tag{16}$$

The net power output of the plant in question is:

$$w_{net} = w_t - w_p = \big(m_1(h_1-h_2) + (m_1-m_2)(h_2-h_3)\big)\eta_t\eta_{ge} - \frac{m_5(h_5-h_4)}{\eta_p} - \frac{m_8(h_8-h_7)}{\eta_p} \tag{17}$$

The work output related to solar energy is:

$$w_{solar} = \frac{w_{net}q_{solar}}{q_{solar}+q_{biomass}} \tag{18}$$

The work output related to biomass energy is:

$$w_{biomass} = \frac{w_{net}q_{biomass}}{q_{solar}+q_{biomass}} \tag{19}$$

The thermal efficiency of the cycle is:

$$\eta_{cycle} = \left(\frac{w_{net}}{q_{solar} + q_{biomass}}\right) \times 100 \tag{20}$$

The fuel efficiency is:

$$\eta_{fuel} = \left(\frac{w_{net}}{m_{biomass} PCI}\right) \times 100 \tag{21}$$

The thermal efficiency of the hybrid plant is:

$$\eta_{thermal} = \left(\frac{w_{net}}{m_{biomass} LHV + I_b A_{total,c}}\right) \times 100 \tag{22}$$

Considering the discussed scenario, the boiler used in the combustion process of sugarcane bagasse, as shown in Figure 1, has an efficiency of 60%. This parameter is crucial for calculating the mass flow rate of biomass. Therefore, with the established equations, the mathematical model of the hybrid plant is defined.

2.4 Solar collector

Heliothermal technologies involve mechanisms for converting direct solar radiation into electrical energy and are part of Concentrated Solar Power (CSP) systems. From this perspective, parabolic trough collectors (PTC) are the most widely used heliothermal technology in the market. Their structure consists of a curved reflective material sheet in a parabolic shape and a focal line integrated with the receiver, which is coupled to a black metal tube covered with a glass tube to minimize heat losses. Thus, the incident solar radiation on the reflector is reflected onto the receiver tube, which in turn heats the fluid circulating through it (Kalogirou, 2009). Typically, the most commonly used fluid in parabolic trough systems is a heat transfer fluid (HTF), such as molten salt and Therminol-VP, or water in the case of direct steam generation systems.

Based on the typical days of each month proposed by Klein (1977), as presented in Table 1, the data for direct normal irradiance, global horizontal irradiance (GHI), and ambient temperature were extracted using the System Advisor Model software for each typical day. Therefore, the selection of a strategic day, aiming to avoid oversizing and undersized, used the solar noon DNI for each typical day of the cities. The analysis involved eliminating 5% of the highest values and considering only DNI values greater than 250 W/m².

Table 1. Average days for each month (Klein, 1977).

Typical days	
Month	**Day**
January	17
February	16
March	16
April	15
May	15
June	11
July	17
August	16
September	15
October	15
November	14
December	10

Figure 2 shows the normal direct irradiance of cities. According to the adopted approach, the corresponding days for the established conditions were July 17, 2020, for João Pessoa City, September 14, 2020, for Coremas City, and October 15, 2020, for Santa Luzia City. The direct normal irradiance for each chosen typical day in the cities exhibits variations throughout the 24 hours period due to meteorological factors such as cloud cover and rainfall.

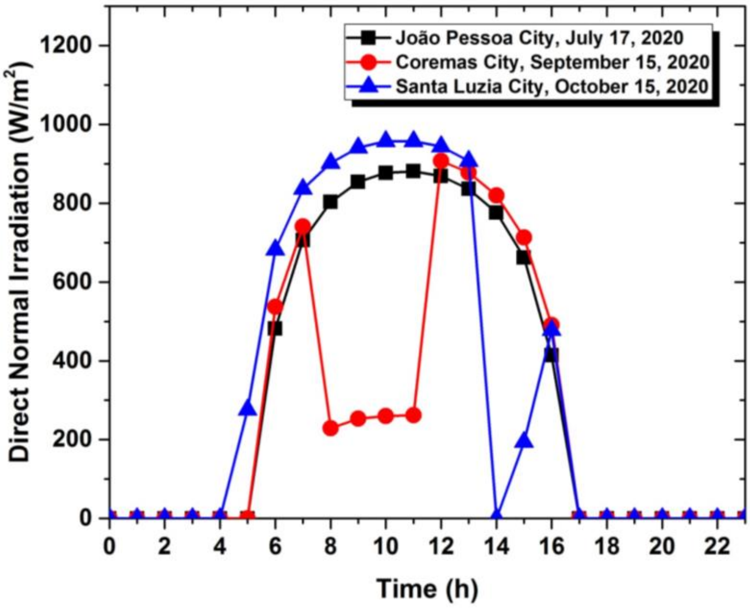

Figure 2. Normal direct irradiance of cities.

Figure 3 shows the ambient temperatures for each city during the selected typical days. The city with the lowest temperature range is João Pessoa, due to its high humidity and the climatic effect of maritime influence, resulting in a small temperature variation. Still, Coremas and Santa Luzia, located inland in Paraíba, are affected by the climatic effect of continental influence, leading to a larger temperature range. The city with the highest temperatures is Coremas.

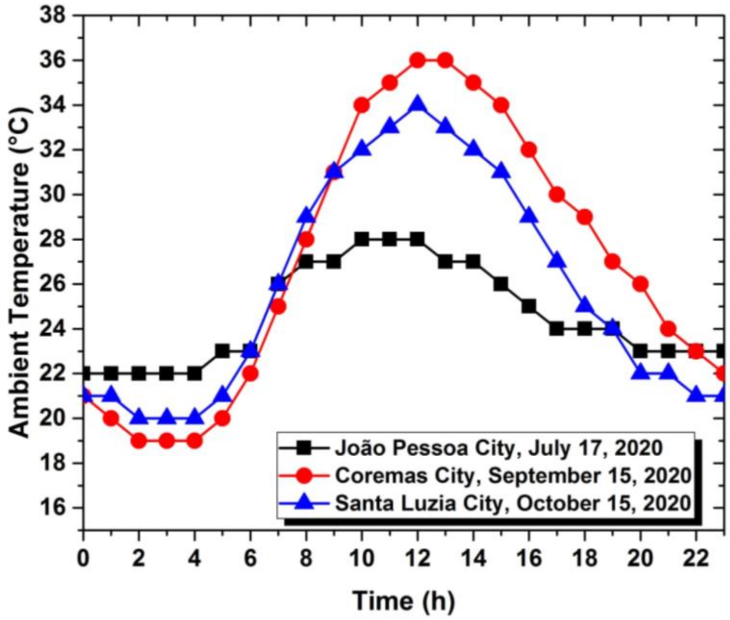

Figure 3. Ambient temperature of cities.

2.5 Biomass

Biomass, when used as an energy input, possesses a flexible and adaptable nature to the technology involved in the process. Considering the potential pollution associated with most thermal power plants, biomass emerges as a renewable fuel capable of mitigating the impacts and bringing advantages for local revenue generation (Lopes et al., 2019). In the Brazilian scenario of 2022, 35.03% of thermal power plants operate with biomass, with approximately 73.24% of this biomass being derived from sugarcane bagasse (ANEEL, 2022).

The statistical data from the Brazilian Institute of Geography and Statistics (IBGE) indicate an increase in the production value of sugarcane between the years 2017 and 2021. The quantity of sugarcane produced was approximately 715,659,212 metric tons, with a harvested area of 9,970,958 hectares and an average yield of 71,774 kg per hectare for the year 2021 (IBGE, 2021).

Table 2. Elemental analysis of sugarcane bagasse.

References	**Carbon % (C)**	**Hydrogen % (H)**	**Nitrogen % (N)**	**Sulfur % (S)**	**Oxygen % (O)**	**Ashes % (A)**
Jenkins *et al.*, 1998	48,64	5,87	0,16	0,04	42,82	2,44
Da Silva, Gonçalves and Freitas, 2016	44,8	5,35	0,38	0,01	39,55	9,79
Gomes, Martelli and Silva, 2013	45,05	4,86	0,68	3,05	42,71	3,65
Grotto et al., 2021	44,25	7,01	0,36	-	47,43	0,95
Average value	**45,69**	**5,77**	**0,40**	**0,78**	**43,13**	**4,21**

According to Cortez et al. (2008), the elemental analysis of a compound is one of the key characteristics of fuels that is relevant for understanding the combustion process. In elemental analysis, the mass percentages of each of the elements present in the sample are determined. In the case of biomass, this typically includes carbon (C), hydrogen (H), sulfur (S), oxygen (O), nitrogen (N), and chlorine (Cl). Therefore, using Table 3, it is possible to find an average value for the elemental analysis of sugarcane bagasse as reported in the literature.

The higher heating value (HHV) refers to the calculated combustion heat assuming that all water in the products underwent the condensation process, so that the reaction releases the maximum amount of energy. On the other hand, the lower heating value (LHV) assumes that the water in the products remains in the vapor state (Turns, 2013).

2.6 Input parameters table

Table 3 presents the input data used in the SAM and EES software for cycle simulation. Through these and the subsequently established equations, the cycle efficiency, hybrid plant efficiency, and thermal efficiency were determined.

Table 3. Elemental analysis of sugarcane bagasse.

Input data				
		Cities		
Parameters	Unit	João Pessoa – PB	Coremas – PB	Santa Luzia – PB
Longitude	°	-34,8530659	-37,9415774	-36,92345117
Latitude	°	-7,1418009	-7,0171179	-6,871027994
Representative day	-	17 July	15 September	15 October
Hour	hour	solar noon	solar noon	solar noon
DNI	W/m^2	864	907	944
GHI	W/m^2	857	816	1054
Ambient temperature	°C	28	36	34
Biomass	-	Sugarcane bagasse	Sugarcane bagasse	Sugarcane bagasse
LHV	kJ/kg	14790	14790	14790
Collector type	-	Parabolic trough	Parabolic trough	Parabolic trough
Inlet temperature	°C	450	450	450
Pressure	bar	40	40	40

The data regarding biomass type, LHV, solar collector, turbine inlet temperature, and pressure are the same for all three locations. Thus, the only parameters that varied according to each city were those sensitive to a specific region, such as latitude, longitude, representative day, DNI, GHI, and ambient temperature.

3. RESULTS AND DISCUSSION

3.1 Case study for cities in Paraíba

The study of the hybrid plant associated with the equation of each thermodynamic process is responsible for characterizing the cycle. Based on the input parameters, the cycle efficiency, fuel efficiency, and hybrid plant efficiency were analyzed for the three selected cities.

Figure 4 shows the graph for the city of João Pessoa. It shows a consistent cycle efficiency throughout the entire analysis period. Still, fuel efficiency was the most sensitive to the cycle's operation, and the hybrid plant efficiency also exhibited variations throughout the day.

The cycle efficiency remained at 26.53% throughout the entire day. This consistency is expected since this parameter depends only on the network produced by the cycle and the heat from the solar collector and biomass, which are values that do not change according to the plant's operation.

In turn, the fuel efficiency at 5 AM is 15.92%, reaching its peak at noon when the DNI is most significant. At that moment, the efficiency reaches 31.84%, but it decreases after noon. The behavior of fuel efficiency is influenced by the biomass mass flow rate supplied to the boiler. From 5 AM to 12 PM, there is a reduction in biomass generation due to the gradual operation of the solar plant. As a result, at noon, both plants operate at half-load to complement each other, resulting in maximum fuel efficiency. For the rest of the day, the DNI decreases along with the efficiency of the solar collectors, requiring a greater contribution from biomass. Thus, the fuel efficiency returns to 15.92%.

In contrast, the hybrid plant efficiency decreases as the solar plant's contribution increases since this parameter depends on irradiance and collector area. Therefore, higher irradiance corresponds to a larger collector area. In this manner, the hybrid plant efficiency is 15.92% at 5 AM and decreases to 14.81% at noon.

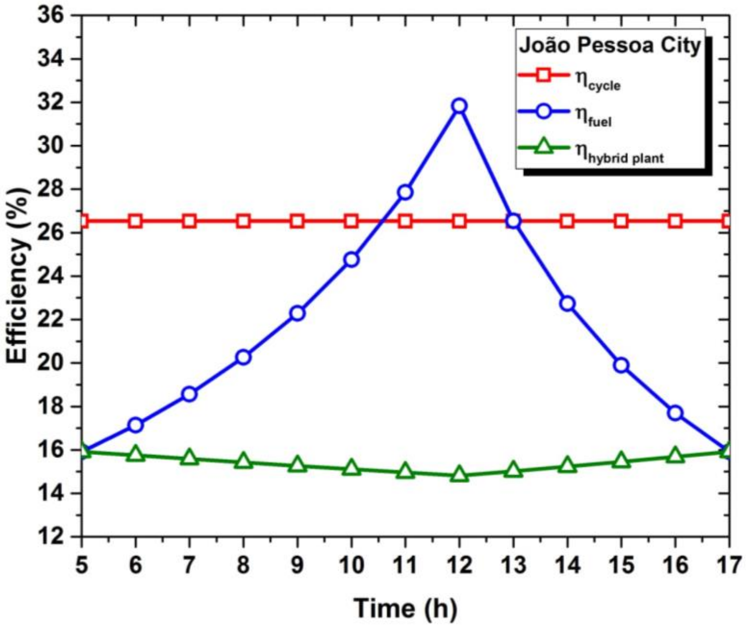

Figure 4. Efficiencies for the João Pessoa City.

Figure 5 shows the graph for the city of Coremas City. Similar to the graph for João Pessoa City, it is evident that there is a constant value for the cycle efficiency throughout the analyzed interval. Furthermore, in this case, fuel efficiency was also the most sensitive to the cycle's operation, and the hybrid plant efficiency exhibited changes throughout the day.

The cycle efficiency remained at 26.53% throughout the entire day. The fuel efficiency at 5 AM is 15.92%, reaching its peak at noon when it reaches 31.84%. Considering that the hybrid plant efficiency depends on irradiance and collector area, its value at 5 AM is 15.92% and it reaches its minimum of 15.54% at noon.

Figure 6 shows the graph for the city of Santa Luzia City. This city exhibits the same pattern as Coremas City and João Pessoa City, where a constant value for the cycle efficiency can be observed, fuel efficiency is sensitive to the cycle's operation, and the hybrid plant efficiency undergoes changes throughout the day.

In the same manner, as the other two cities, the cycle efficiency remained at 26.53% throughout the entire day. The fuel efficiency at 5 AM is 15.92%, reaching its maximum value at noon when it reaches 31.84%. On the other hand, the hybrid plant efficiency at 5 AM is 15.92% and reaches its minimum value of 13.84% at noon.

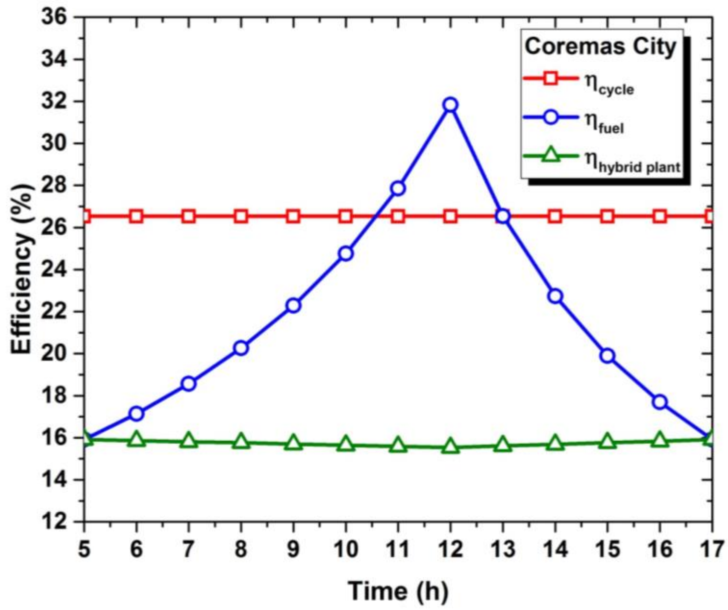

Figure 5. Efficiencies for the Coremas City.

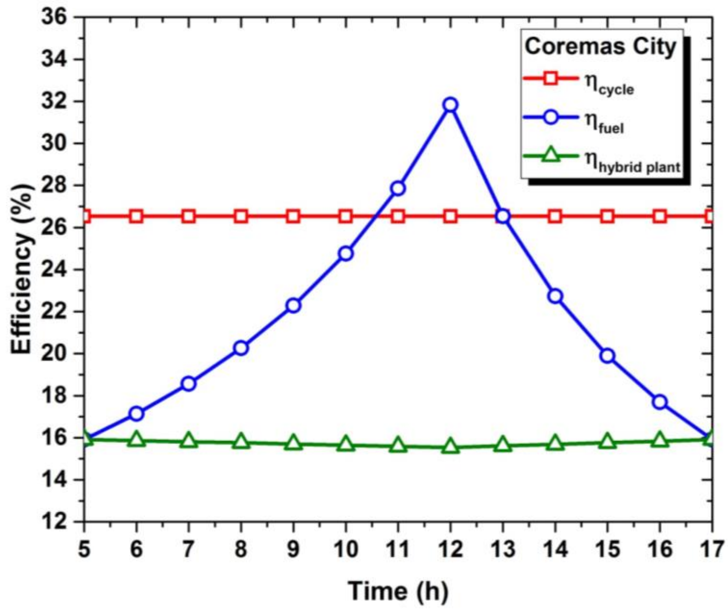

Figure 6. Efficiencies for the Santa Luzia City.

The consumption of sugarcane bagasse biomass in this hybrid solar/biomass system varies from 0.32 kg/s to 0.16 kg/s from 5 AM to 12 PM. On the other hand, from 12 PM to 5 PM, consumption behaves inversely, increasing from 0.16 kg/s to 0.32 kg/s. During the nighttime period, consumption remains constant at 0.32 kg/s. These values are applied to all three cities since the calculation of the maximum biomass flow rate depends on fixed parameters such as biomass heat content, LHV, and boiler efficiency. These respective factors are not influenced by geographical location and are determined by pre-established data related to the boiler, biomass, and thermodynamic cycle.

4. CONCLUSION

The perspective of integrating a hybrid power plant in the cities of Paraíba aims to enhance the cycle efficiency, meet the intermittent periods of energy sources, and promote the local economy. With the water/steam, air, and gas circuit operating in a simple regenerative Rankine steam cycle and incorporating parabolic solar collectors (CSP) and sugarcane bagasse biomass, the system met the demands of each location.

The sizing of the power plant for each city is based on the strategic choice of the DNI for a representative day to determine the required mirrored area for the installation of the collectors. Based on the results, it can be concluded that the cycle efficiency and fuel efficiency for the cities of João Pessoa, Coremas, and Santa Luzia are the same since these parameters do not vary according to the city. However, the hybrid plant efficiency is sensitive to each location as it depends on factors such as DNI and collector mirror area, and thus, Coremas City has the highest hybrid plant efficiency. Finally, this study contributes to the intensification of research related to thermosolar systems in the context of power generation in Brazil.

5. ACKNOWLEDGEMENTS

The authors acknowledge the support of the Paraiba State Research Foundation - FAPESQ Brazil (Term n° 066/2023, Edict n° 19-2022).

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7. RESPONSIBILITY NOTICE