

COBEM-2023-1431: THERMODYNAMIC CYCLE ANALYSIS AND COMBINED HEAT AND ELECTRICITY GENERATION WITH SOLAR ENERGY.

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Abstract: Energy cogeneration through solar thermal systems is an efficient solution to meet industrial energy demand. In Brazil, with its solar potential and the need for renewable sources, there are opportunities to take advantage of this resource. One study presented a model of a cogeneration plant in Surubim-PE, which generates electricity and hot water. Using parabolic trough solar concentrators, the SAM simulator calculates the energy absorbed in the region to produce electricity in an organic Rankine cycle, with Benzene as the working fluid due to its efficiency at temperatures below 100°C. The EES software simulates the organic cycle, which consumes 98% less water than conventional plants. Residual thermal energy is used to produce hot water in processes in the textile industry. The implementation of this system has practical and sustainable applications, contributing to the reduction of the emission of harmful gases to the environment. Solar thermal energy offers significant potential that can be exploited to meet industrial energy demands and promote the transition to a cleaner and more sustainable energy matrix.

Keywords: Cogeneration, Solar thermal energy, Concentrated solar systems, Pollution reduction, Organic Rankine cycle, Renewable energy.

1. INTRODUCTION

In the year 2021, according to data from the EPE (2022), the amount of energy available internally in the country reached 301.5 million equivalent tons of oil (Mtoe), presenting a growth of 4.5% in relation to the previous year. However, even with this increase, there was a decrease in the contribution of renewable sources in the energy matrix due to the reduction in hydroelectric power generation caused by water scarcity and the increased use of thermoelectric plants. On the other hand, the generation of electricity from wind and solar sources, as well as the use of biodiesel, helped maintain the proportion of renewable sources in the Brazilian energy matrix at a high level of 44.7%, significantly exceeding the global average. Where in Figure 1 is shown the share of renewables in the domestic energy supply. Energy consumption in industry has increased by 3.6% compared to 2020. In addition, the energy matrix used by industry presented a proportion of 58% of renewable sources, says the EPE (2022) in the National Energy Balance.

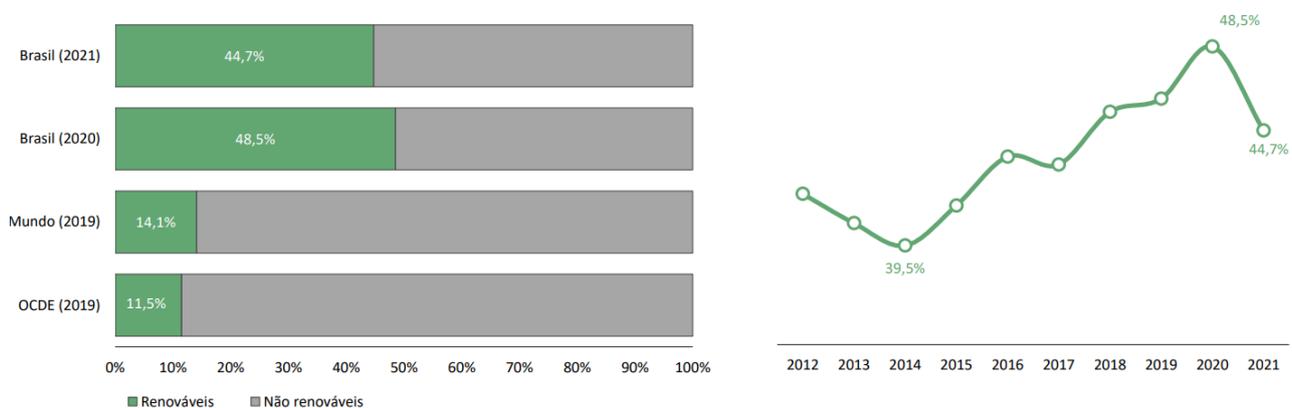


Figure 1. Participation of renewables in the Internal Energy Supply.
font: EPE(2022).

According to Müller *et al.* (2014), industrial process heat demands worldwide cover a wide range of temperatures, from low temperatures (around 30 °C) to high temperatures (above 1300 °C). The authors also note that about 30% of the energy is required in the range 0 to 200 °C, with a further 8% up to 400 °C. Thus, approximately 38% of the industry's energy needs could be met by CSP.

SOURCES (%)	2013	2014	2015	2016	2017	2018	2019	2020	2021
NATURAL GAS	11	11	11,1	10,6	10,6	11,4	10,5	8,9	10,27
Steam Coal	4.1	4.5	4.6	3.9	4.3	4.7	4.4	4	4.3
Firewood	8.8	9	8.8	8.7	8.7	9.1	9.5	8.8	9
Sugar Cane Bagasse	19.5	18.5	18.3	21.1	20.3	16.4	16.7	22.1	18.2
Other Renewable	6.9	7.3	8	8.6	8.7	9.7	9.5	9.6	9.8
Other Non-Renewable	0.4	0.4	0.3	0.3	0.3	0.3	0.3	0.3	0.3
Fuel Oil	3	3	2.7	2.8	2.3	1.6	1.7	1.7	1.8
Coke Gas	1.4	1.4	1.4	1.3	1.4	1.5	1.4	1.3	1.5
Coal Coke	8.9	8.9	9.4	8.5	9.1	9.7	9.2	8.4	9.3
Electricity	20.6	20.5	20.2	20.4	20.4	21.5	21.5	20.8	21.6
Charcoal	4.2	4.1	4.2	3.6	3.7	4.1	4.4	4.2	4
Others	11.2	11.4	11	10.2	10.2	10	10.9	9.9	10
Total	100	100	100	100	100	100	100	100	100

Table 1. Energy sources of the industrial sector in Brazil.

font: EPE(2022).

In the case of jeans, after the processing processes, the product goes to the industrial laundries, with a significant of the Local Productive Arrangement (APL) of Apparel of the Pernambuco Agreste, which includes 13 municipalities, especially Caruaru, Santa Cruz do Capibaribe, Surubim, and Toritama. In the region covered by this APL, it is estimated that there are about 300 industrial laundries, regularly established and clandestine, which perform operations of desizing, washing, dyeing, bleaching and ironing processes for jeans. In all these companies the production of hot water for the processes is made by direct steam injection in water tanks, initially at room temperature, and that must reach temperature, and that should reach from 60°C to 90°C, depending on the process and the company.

The clothing industry in the Agreste gained prominence and became economically important due to its growth over the years. Specifically, the cities of Toritama, Santa Cruz do Capibaribe and Caruaru emerged in this segment and today lead the fashion industry in the region. Besides the cities of Toritama, Santa Cruz do Capibaribe and Caruaru, there are other cities in the Agreste region that play an intermediary role in textile production, such as Surubim. Located in the mesoregion of the Northern Agreste and in the micro-region of Alto Capibaribe, Surubim is approximately 124 km from the capital of Pernambuco. Although it has not reached the same level of prominence as the aforementioned cities, Surubim contributes to the region's textile production chain and plays a significant role in this sector. Surubim is the fourth largest producer in the Polo de Confecções do Agreste, alongside Caruaru, Santa Cruz do Capibaribe, and Toritama, accounting for about 10% of state production, according to SEBRAE (2013). And according to research by Cordeiro (2015) the city had about 454 establishments linked to the textile industry.

The objective of this work is to simulate the generation of electricity and waste heat from a parabolic trough plant in the city of Surubim-PE. Where this heat will be used in the processing of jeans in a local factory, knowing the solar potential that the agreste region of Pernambuco has and as already mentioned the importance of the textile industry in the city of Surubim.

2. METHODOLOGY

In Figure 2, the scheme of the heliothermal plant is presented, which has been modeled for electricity generation and harnessing residual heat for hot water production in the jeans washing process during the beneficiation stage. On the left side of the Figure, there is a field of concentrator collectors that provide heat directly to a thermal energy storage system. The specific details of this storage system have not been specified and are treated in a generic manner. It was included in the system with the main purpose of ensuring the stability and continuity of the thermal fluid supply at a temperature of 200 °C when it returns to the concentrator field.

The solar field technology is a crucial component of the system; however, in order to generate electricity, it needs to be integrated with a thermal machine that operates on a thermodynamic cycle. In this particular case, an organic Rankine cycle (ORC) with Benzene as the working fluid will be employed because, according to Mchahan (2006), solar plants utilizing ORC are characterized by their compactness, lower cost compared to traditional systems, and higher efficiency at lower temperatures ranging from 80 to 400 °C, which aligns with the temperature range provided by the solar collectors.

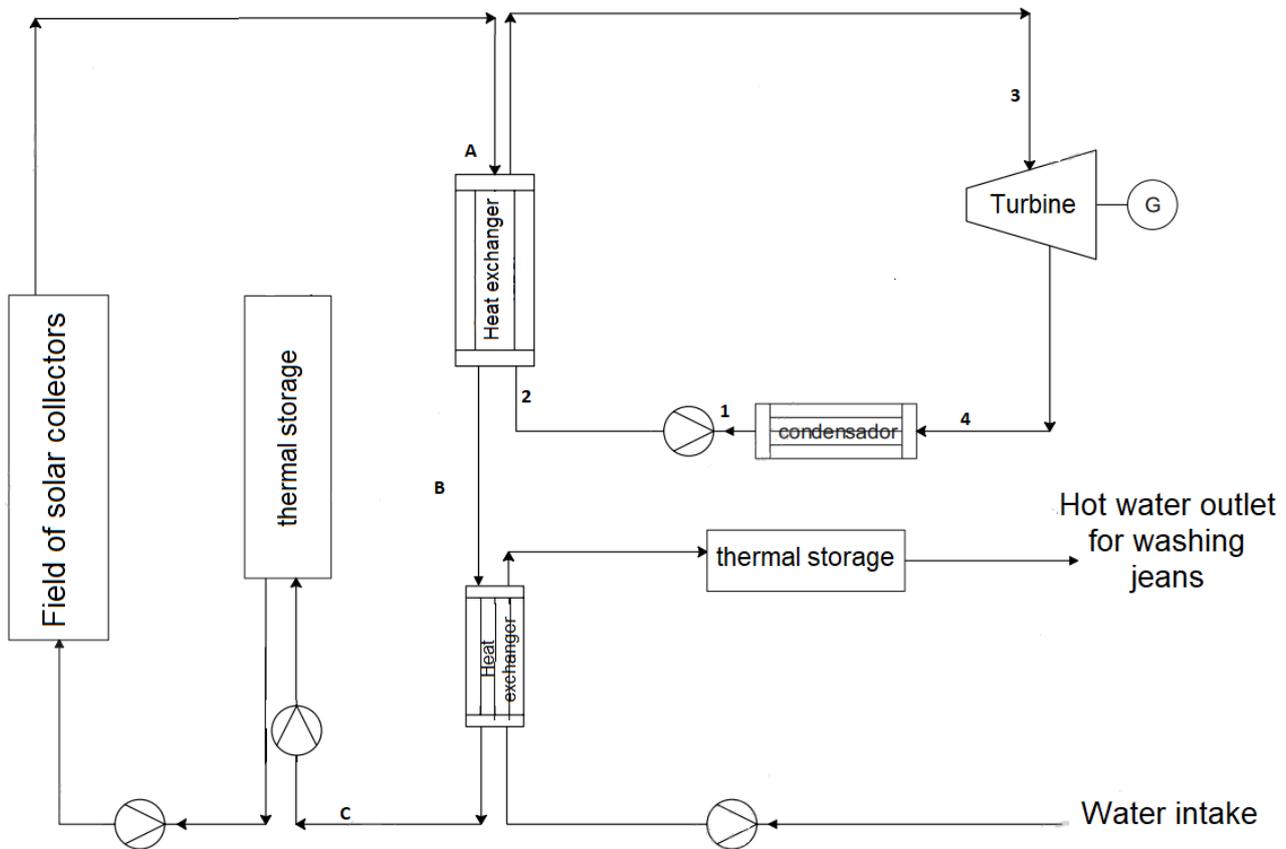


Figure 2. Model of solar plant.
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2.1 Simulation Methodology

The study was based on simulations using the free System Advisor Model (SAM) software, developed by NREL (2022), on the "Parabolic Trough (Physical)" model. Simulations were conducted for commercially available parabolic trough-type collectors, covering a temperature range of 200 °C to 300 °C. Environmental and geographic data specific to the city of Surubim-PE were obtained directly from the SAM's built-in library and was implemented 800 W/m² for DNI.

2.2 Specifying System Components

An essential aspect of the project involves the selection of the fundamental solar field elements in the cogeneration system, including the concentrator, heat transfer fluid, and absorber tube. The heat transfer fluid chosen was Therminol VP-1 because of its temperature and pressure properties suitable for the expected operating range. Therminol VP-1 is capable of operating in temperatures ranging from 12 °C to 400 °C and pressures from 1.0 bar to 33.1 bar according to the manufacturer THERMINOL.

The collector model selected is the LS-2, developed by LUZ Corporation, a company specialized in PTC components. The decision to use this model was motivated by the recent work of Bergel and Garcia (2020), which showed promising results in simulations with this specific configuration. The LS-2 collectors have an aperture width of 5 meters, a length of 49 meters, and a reflective area of 235 square meters as shown in Table 2. The mirrors used are made of tempered glass. In addition, these collectors are equipped with a tracking system and automatic safety devices. The heat collector element (HCE) used was Solel UVAC Cermet, with an absorbance of 0.96 as it appears in the SAM library.

Then with the data implemented in SAM the software itself does the simulation and from the return data the heat transfer fluid (HTF) output temperature of the solar field is used. Then these values are used to simulate the energy production with the ORC in the other software used, the Engineering Equation Solver (EES) that was used because its library already contains the properties of the organic fluid used (Benzene).

Table 2. LS-2 Collector Parameters.

Parameter	Value
Opening width [m]	5.0
Length [m]	49.0
Reflexive Opening [m ²]	235.0
Optical efficiency	0.871
Reflectance	0.935

font: Adapted from Bergel and Garcia (2020).

2.3 Modeling in EES

In the cycle, the processes are considered to be isentropic and only the efficiencies of the turbine, pump and generation are taken into account. In the EES, the ORC was designed to produce around 1.0 MW and a heat exchanger (considered ideal) between the organic fluid and the thermal fluid was used to heat the fluid. After defining the working fluid, the following input data was defined in Table 3. However, the processes are only defined when the HTF outlet temperature is greater than 270°C.

Table 3. ORC Input Parameters.

Parameter	Value
Organic Fluid Flow [kg/s]	8.0
Turbine efficiency	0.75
Pump efficiency	0.80
Generator efficiency	0.95
Heat exchanger efficiency	0.82
Ambient temperature [°C]	25.0
Hot water temperature [°C]	70.0
Hot water flow [kg/s]	20.0
Thermal fluid flow [kg/s]	24.0
Specific heat of the thermal fluid	2.26

font: Author.

After defining the input data, the output temperature of the HTF is used to define the heat generated by the plant and the benzene evaporation temperature using an interactive function that compares the fundamental equation of calorimetry with the heat of the cycle, thus defining the evaporation temperature of the organic fluid. The ORC superheat temperature is then calculated using Equation 1.

$$T_3 = T_{ev} + \frac{Q_0 - ((\dot{m}_{orc}c_{p_{orc}}(T_{ev} - T_0)) + (\dot{m}_{orc}h_{orc}))}{\dot{m}_{orc}c_{p_{orc}}} \quad (1)$$

Where: T_3 (°C): Working fluid superheat temperature, T_{ev} (°C): Cycle working fluid evaporation temperature, \dot{m}_{orc} (kg/s): Mass flow rate of the fluid organic, $c_{p_{orc}}$ (kJ/(kg K)): Specific heat of the organic fluid at constant pressure, h_{orc} (kJ/kg): Enthalpy of vaporization. And then the conventional calculations of a rankine cycle are made.

After calculating the electricity production values, the HTF waste heat is used to calculate the production of hot water that will be used in the jeans washing process in a textile industry, where the production of 20 kg/s of water at a temperature of 68°C was estimated. To do this, it is necessary to know the temperature of the thermal fluid at B " T_B " (after the Rankine cycle heat exchanger), so this temperature is obtained from Equation 2.

$$T_B = T_{HTF} - \frac{\dot{m}_{orc}c_{p_{orc}}(T_3 - T_1)}{\dot{m}_{HTF}c_{p_{HTF}}} \quad (2)$$

Similarly, the temperature of the HTF at point C " T_C " (after the hot water production heat exchanger) is calculated using Equation 3. Where m_{water} (water flow) is 20 kg/s, $c_{p_{water}}$ (specific heat of water) is 4.18 kJ/(kg K) and T_{lava} (washing water temperature) is 70°C and T_{amb} (water ambient temperature) is 25 °C.

$$T_C = T_B - \frac{m_{water}c_{p_{water}}(T_{lava} - T_{amb})}{\dot{m}_{HTF}c_{p_{HTF}}} \quad (3)$$

Furthermore, some conditions were set for the final simulation, which are: it will only generate energy if the temperature of the HTF at the input of the system (T_0) is higher than 220 °C, and it will also only produce hot water if the

temperature of the thermal fluid after the output of the ORC heat exchanger is higher than 220 °C. These conditions were made to ensure the initial assumption that the final temperature of the HTF outlet (which enters the solar collector field) is 200 °C.

3. RESULTS AND DISCUSSION

With this, as we have a lot of data, hour by hour for a whole year, and an almost periodic behavior was observed, to facilitate understanding a graph of the variation of the HTF temperatures inside the cogeneration system and also of the energy and hot water production during the period from 06:00 to 21:00 hours of a random day was made. Where the Figure 3 shows the graph of the HTF temperature variation where the results were as expected, in the way that when the radiation starts to increase at 07:00 am the fluid temperature starts to rise and remains almost constant throughout the day and drops again around 05:00 pm. In this way, as shown in Figure 4 there are the graphs of electricity production and hot water production, where the production of electricity occurs between the hours of 08:00 am and 04:00 pm, while the production of hot water at a temperature of 70°C occurs between 08:00 am and 04:00 pm.

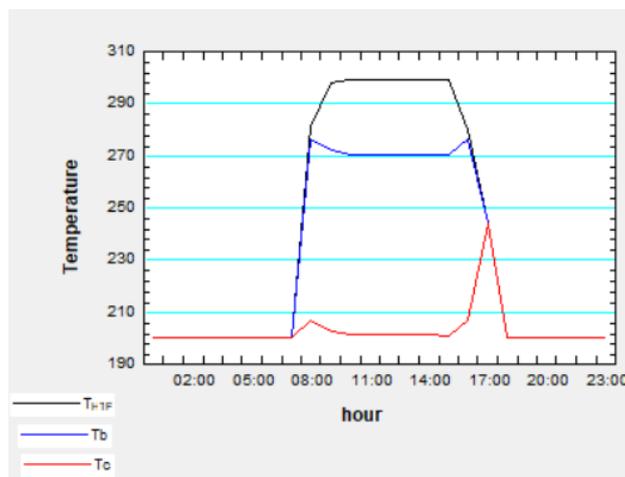


Figure 3. Graph of HTF temperatures during the day.
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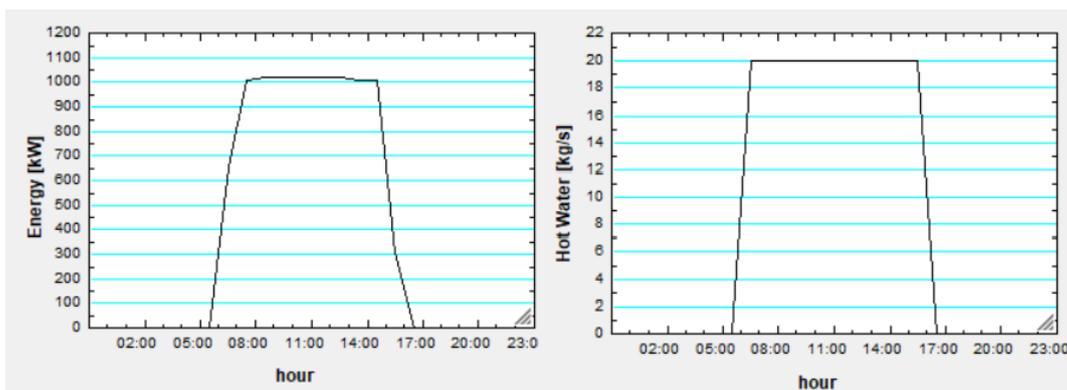


Figure 4. Energy and hot water production graphs.
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4. CONCLUSION

Based on the results obtained from the simulations, it can be concluded that the proposed system can produce 0.9 MW of electricity on average and 20 kg/s of hot water at a temperature of 70 °C every day from 08:00 to 16:00. From ?, in a study of 46 laundries in the Toritama-PE region, which is close to the case study, 70% of the laundries burn firewood to heat the water, which is one of the causes of deforestation. It was also found that 30% burn leftover fabrics as a secondary source of energy, so both types of fuel emit greenhouse gases and, in the case of firewood, this exacerbates the issue of deforestation in the Caatinga biome. Thus, the advent of solar collector technology adds a reduction in pollutants to the process, since there will be a reduction in the consumption of firewood and, consequently, a reduction in the deforestation of local vegetation areas.

Furthermore, in the current context of the textile industry, where concern for sustainability is on the rise and economic conditions are undergoing constant change, the strategy of integrating electricity generation and hot water production emerges as an intelligent and conscious solution.

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