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OPTIMIZATION AND THERMOECONOMIC ANALYSES IN DUAL PLANTS TO THERMAL DESALINATION WITH INTEGRATED SOLAR RANKINE CYCLE FOR DEVELOPMENT IN SÃO MATEUS – ES

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Abstract. *In drought times, the residents of São Mateus, in Espírito Santo, live with the high salinity in the water distributed for Supply Water and Sewage System (SAAE). It is justified due to low level from the Cricaré river in these times and, hence, the sea water goes to over to collect point to water treatment, as well as the alternative of the city was the construction of artesian posts. Another consequence of dry times is the increase of electric energy cost in Brazil, due to the incidence of tariff flags, when the emergency thermoelectric should be to turn it on. Then, a possible alternative is the use of an Integrated Solar Rankine Cycle (ISRC) to energy generation and a thermal desalination process to solution of these problems simultaneously. Thus, aims in this paper the evaluation and optimization of thermal parameters of a thermal plant to desalination type multi-effect (MED) with 4 different setups to the Rankine cycle integrated with parabolic solar collectors to power supply. Therefore, in this paper is used the genetic algorithms to the optimization method in the software Engineering Equation Solver (EES). It was defined as the decision variables the inlet pressure of turbine and condenser, isentropic efficiency of turbine and the pumps, the rate of steam to the desalination chamber, the temperature variation in the superheat and the collector area. It was used to the parabolic collectors the therminol VP1, due to its greater temperature to operation than others thermals oils like therminol XP and therminol 66, for example. Another objective in this paper is the exegetics and monetary costs analyses to electric energy and fresh water production using the H&S model, with annual average of 600W/m² radiation emission and 2,400 m³/day to fresh water production. With the first setup, it was possible to reach 8.15 R$/MWh and 0.75 R$/m³ to energy and fresh water production, respectively, with 12.41 MW of net power and a collector area of 90,279 m².*

Keywords: *Desalination, ISRC, Costs, Optimization.*

1. INTRODUCTION

Seasonally, in times of drought, the municipality of São Mateus - ES lives with the reality of high salinity delivered by the Water Supply and Sewage System (SAAE) in the homes of the population. This occurs due to the low level of the Cricaré River and the consequent advance of the sea through the mouth of the river beyond the water collection point for treatment. According to the World Health Organization (WHO), the salinity limit of water should not exceed 250 ppm. In the year 2019, in the month of October fresh water was delivered with salinity up to 4400 ppm (Goliver, 2019). As an alternative, the public authorities have drilled several artesian wells strategically scattered in some points of the city to supply the population in these critical periods, given that, consequently, it becomes the main alternative of the municipality to solve this problem. Thus, the use of other resources to promote the supply of fresh water to the population of the city becomes feasible.

The MED (multiple effect distillation) is a desalination process by vacuum distillation, in which heat is added to salt water, promoting steam evaporation with pure water and the resulting salt separation (Santos, 2005). This system has the capacity to produce desalinated water up to 15,000 m³/day and has a higher global yield, and the same has a lower electrical consumption, all this when compared to the MSF (Multi-Stage Flash), according to Uche *et al.* (2002b). It has the advantage of operating at lower temperatures due to the use of a vacuum system, which reduces the risk of surface corrosion. The main source of energy consumption of the MED system is in the form of heat, since it consumes a small amount of electricity to power pumps and other auxiliary equipment (Santos, 2005).

The use of an Integrated Solar Rankine Cycle (ISRC) has used to reduce the environmental impact (Cavalcanti *et al.*, 2015) and the hence electric energy production. According to Nishit (2014), there are 4 different technologies for CSP (Concentrating solar power), in which one can mention the parabolic trough collector (PTC), linear Fresnel reflector (LFR), solar power tower (SPT) and paraboloid dish. Among those mentioned, the PTC presents greater stability (Nishit, 2014). According to Santos (2005), desalination processes are characterized by high energy consumption, whether in the form of electricity or heat. Thus, this is the advantage of using a power generation plant combined with a desalination process.

Based on the Darwinian model of evolution of living beings, the G.A (Genetic Algorithm) method has become one of the main optimization tools, mainly due to a possibility in multidisciplinary. This method allows the resolution of complex systems, in quality independent of the area of action (Lopes, 1999), which makes it viable for applications in engineering.

Considered a relatively new science that relates thermodynamic and economic knowledge, according to Dos Santos (2015), thermo-economics can provide tools to solve problems in complex energy systems that may be difficult or even impossible to solve using conventional energy analysis based on the First Law of Thermodynamics (mass and energy balance). Over the years, several thermo-economic methodologies have been developed, which agree that the best way to calculate costs is to use the rational way through the Second Law of Thermodynamics.

Therefore, through thermo-economic methodologies, it aims to compare four cogeneration plant projects with the same products (desalinated water and electricity).

2. METHODOLOGY

2.1 Solar Model

The meteorological data were imported in a spreadsheet format of the São Mateus - ES automatic station, through the National Institute of Meteorology (INMET) website. In this way, it is possible to obtain different meteorological parameters. Figure 1 shows an incident solar radiation distribution in the São Mateus region in July and December from 2020, between 7 and 19 hours. The meteorological data required for thermodynamic modeling for the CSP collector will be: solar radiation, ambient temperature and wind speed.

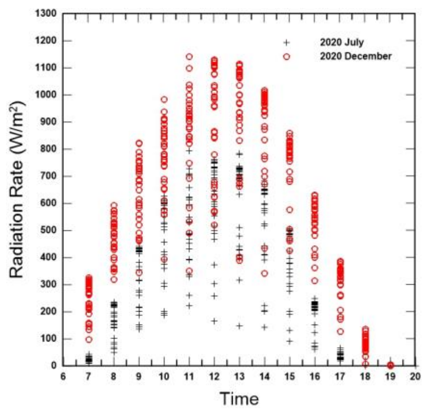


Figure 1. Distribution of solar radiation in São Mateus - ES between the period from July and December 2020 (INMET, 2020).

Therefore, for the current analysis, a solar radiation equivalent to 600 W/m² was chosen, in which it is checked as an average solar radiation in the city of São Mateus-ES during the months analyzed. For the wind speed it was observed that in 2020 the city registered an average speed of 2.93 m/s and an average temperature of 28.8°C (301.8 K).

For the case study, a parabolic solar collector (PTC) is proposed, according to the configuration shown in Figure 2, where there are tubes arranged in series (y), each 20 m long, and parallel lines (x). In this case, shadowing and block effects will not be considered. The number of tubes in parallel lines and in series was obtained with the G.A optimization, where shown in sub-level 2.3.

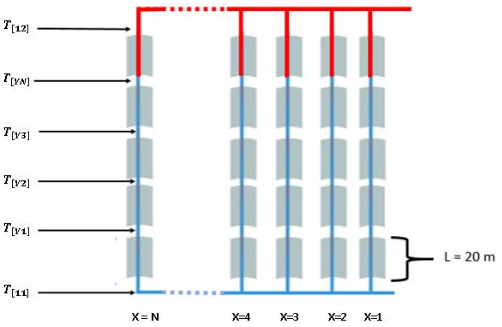


Figure 2. PTC layout.

Table 1. PTC Features.

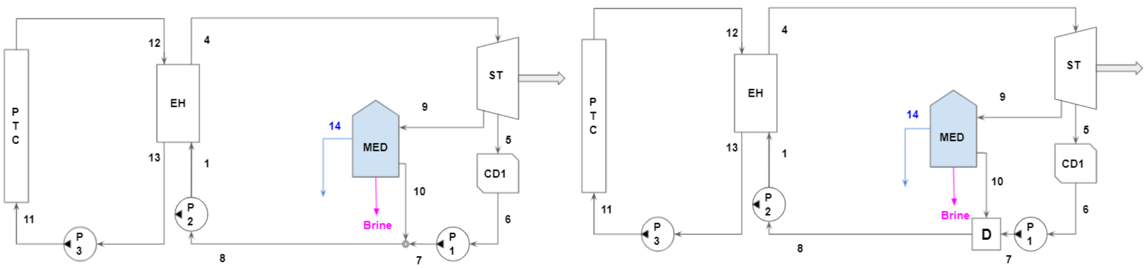
Parameters	**Values**
Aperture (*Ap*)	3.5 m
Receiver outside diameter (D_o)	50 mm
Receiver inside diameter (D_i)	40 mm
Diameter of the glass cover (D_V)	90 mm
Emissivity of glass coating (ε_g)	0.87
Emissivity of the receiver (ε_r)	0.92
Collector length (L)	20 m

The collector consists of two concentric tubes of metal (receiver) and glass (coating), supported by lattice bases. The bases are also responsible for the parabolic reflector support, in which it has a horizontal E-W sun tracking system and orientation of the N-S axis. Between the tubes, there is a vacuum to minimize losses by heat transfer. The thermal fluid will be a thermal oil, Therminol VP1, as so the fluid data are available on the website (Therminol, 2021). The manufacturer does not recommend that the oil temperature exceed 673 K. The heat flow to the CSP collector will be considered constant and the mirror surface will behave as an isothermal surface. Therefore, the heat gain in each tube will be the same.

2.2 Thermodynamic, economic and thermoeconomic models

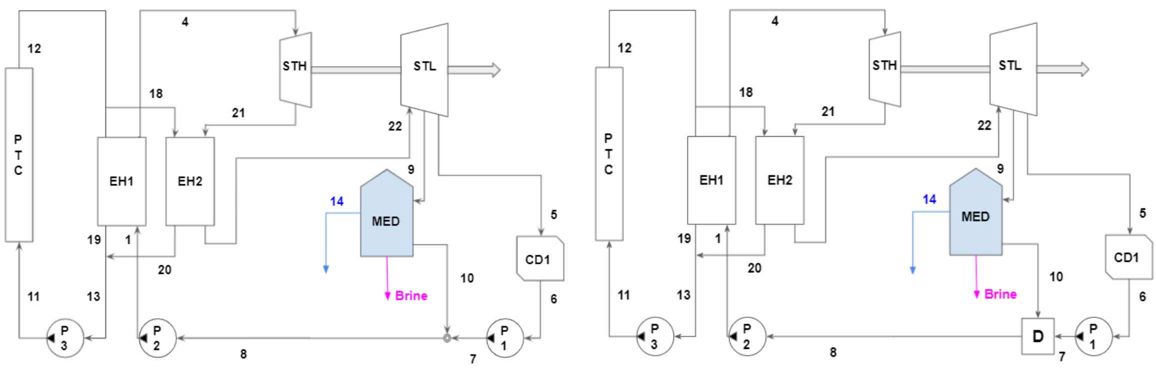
The desalting process consists of a multi-effect distillation desalination process (Multiple Effect Distillation - MED) and it was used a production of 2400 m³/day, 2 kWh/m³ and 18.74 kWh/m³ to electric and thermal specific consumption, respectively, where it was used by Santos (2005) with the model MED-2400.

It was submitted 4 different configurations for Rankine cycle: MED and CSP with basic Rankine cycle (a), MED and CSP with regenerative Rankine cycle (b), MED and CSP with reheat Rankine cycle (c) and MED and CSP with reheat-regenerative Rankine cycle (d). These different forms for the Rankine cycle were adapted from Nishit (2014), and it used PTC as the energy source to power the plant, but not an auxiliary plant for desalination. Therefore, the setups can be analyzed in Figures 3 and 4.



(a) (b)

Figure 3. Project of cogeneration plant (a) MED and CSP with basic Rankine cycle and (b) MED and CSP with regenerative Rankine cycle.



(c) (d)

Figure 4. Project of cogeneration plant (c) MED and CSP with reheat Rankine cycle and (d) MED and CSP with reheat-regenerative Rankine cycle.

The parameters of pressure in the condensing turbines steam, mass flow rate, pressure in the condenser, pumps and turbines efficiency, and variation of superheat temperature were obtained in the optimization in sublevel 2.3. The thermal oil flow is controlled by the maximum temperature allowed by the manufacturer (400 ºC) (623 K) and an inlet temperature in PTC of 200° C (473 K).

The power in the steam turbines and pumps can be calculated according to Eq. (1) and (2).

$$\dot{W}_{ST/P} = \dot{m}_{fluid}(h_{inlet} - h_{outlet}) \tag{1}$$

$$\dot{W}_{Pump3} = \dot{m}_{oil}\frac{\Delta_P.X}{\rho_{oil}} \tag{2}$$

Where $\dot{m}_{oil}$, ρ_{oil} and X are the thermal oil mass flow in a collector tube, oil density and number of collectors in parallel, respectively. The Δ_P is the pressure variation in tubes from collector. The mass rate flow can be calculated tough the Eq. (3) and (4), considering the percentage of the rate flow to desalination (w).

$$\dot{m}_1 = \dot{m}_9 + \dot{m}_5 \tag{3}$$

$$\dot{m}_9 = w.\dot{m}_1 \tag{4}$$

The thermal energy absorbed by the thermal oil in the first tube of the solar collector is given by Eq. (5), which according to Kalogirou (2014) can be equalized by Eq. (6) through the heat removal factor (F_R), where I_{rad} is the direct average radiation rate that affects the PTC mirror, A_{ap} is the solar incidence area of the PTC, T_e the air temperature near the collector, U_L the heat transfer coefficient of thermal losses for the environment, C the concentration factor of the collector, A_r the outer surface area of the receiver and c_p, oil specific heat.

$$\dot{Q}_u = \dot{m}_{oil} \cdot c_{p,oil}(T_{12} - T_{11}) \tag{5}$$

$$\dot{Q}_u = F_R \cdot A_{ap} \cdot \left[I_{rad} - \left(\frac{U_L(T_{12}-T_a)}{C}\right)\right] \tag{6}$$

$$C = \frac{A_{ap}}{A_r} \tag{7}$$

$$A_{ap} = \left(A_p - D_V\right) \cdot L \tag{8}$$

$$A_r = \pi \cdot D_0^2 \cdot L \tag{9}$$

The Figure 5 shows a thermal resistance schematic in a section of the PTC tube in which a constant heat flux ($\dot{Q}_u$) along the length will be considered. An average value of the thermal oil properties will be used between a temperature range of 200 ºC (473 K) to 400 ºC (673 K): density 817.2 kg/m³, viscosity 0.2214 mPa.s, specific heat 2.3140 kJ/kg.K and thermal conductivity 0.0964 W/m.K. In this manner, the temperature at the collector outlet (T_{12}), can be calculated by Eq. (10) by rearranging Eq. (5).

$$T_i = T_{i-1} + \frac{\dot{Q}_u}{\dot{m}_{oil} \cdot c_{p,oil}} \tag{10}$$

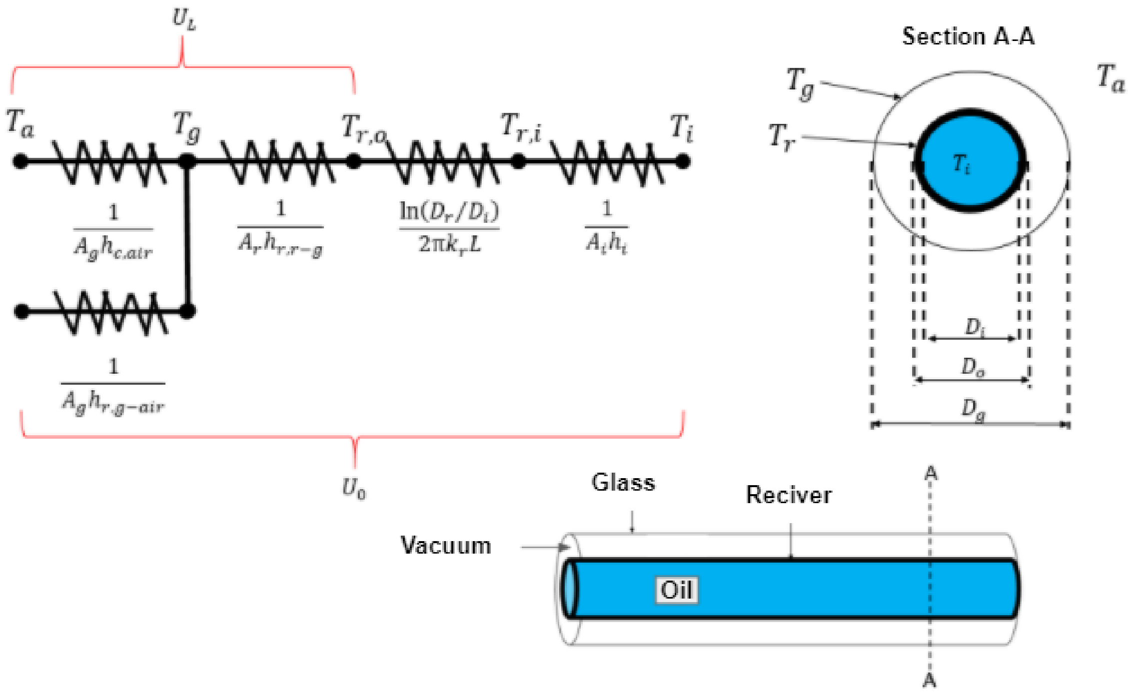


Figure 5. Model of thermal resistance for PTC.

The thermal oil flow in each solar collector line is a function of the oil maximum temperature (T_{12}), which should not exceed 400 ºC. Thus, it is possible to calculate the energy delivered amount by the thermal oil to water by Eq. (11) to the heat exchange from Rankine cycle (a) and (b).

$$\dot{m}_{oil} \cdot c_{p,oil}(T_{12} - T_{11}) = \dot{m}_1(h_4 - h_1) \tag{11}$$

To the setup (c) and (d) of Rankine cycle, it must consider the percentage of oil mass rate flow to the heat exchanger (r), where its values is 25%. However, it can see in the energy balances by Eq. (12) and (13) to heat exchanger 1 and 2, respectively.

$$\dot{m}_{19} \cdot c_{p,oil}(T_{12} - T_{19}) = \dot{m}_1(h_4 - h_1) \tag{12}$$

$$\dot{m}_{18} \cdot c_{p,oil}(T_{18} - T_{20}) = \dot{m}_1(h_{22} - h_{21}) \tag{13}$$

$$\dot{m}_{19} = r.\dot{m}_{oil} \tag{14}$$

For the heat exchangers and condenser, it should be noted that their cost equations, as will be shown below, depend on the thermal exchange area, so that the usual values of heat transfer global coefficient for heat exchangers and condenser will be adopted. Thus, it was adopted U_{EH} = 0.35 kW/m² (oil-steam) and U_{CD} = 1 kW/m² (steam-water), respectively (Çengel, 2009), and it will be possible to determine the areas value of the heat exchangers and condenser through the Eq. (15) and (16).

$$\dot{Q}_o = \dot{m}_{fluid}(h_{inlet} - h_{outlet}) \tag{15}$$

$$\dot{Q}_o = U_i \cdot A_i \cdot \Delta T_{LM_i} \tag{16}$$

Therefore, the logarithmic average temperature for the heat exchangers and condenser can be calculated using Eq. (17).

$$\Delta T_{LM_i} = \frac{(T_{i_1} - T_{o_2}) - (T_{o_1} - T_{i_2})}{ln(T_{i_1} - T_{o_2} / T_{o_1} - T_{i_2})} \tag{17}$$

Where the cooling temperature are 28.8 °C and 33.8 °C in the condenser.

When evaluating the costs of a plant, it is necessary to consider the annual cost associated with the purchase and operation of each plant component. The expressions for obtaining the purchase equipment costs (Z) are presented in Table 3 and the constants in Table 4.

Table 3. Equipment cost functions.

Equipament	***Cost Equation***	***Source***
Collector Solar	$Z = 355 \cdot A_{REA,solar}$	*Cavalcanti et al (2015)*
Condensers	$Z = 156000.(A_{REAcondenser}/200)^{0,89}$	*Frangopoulos* apud *Uche (2000a)*
Steam Turbine	$Z = A \cdot exp\{B \cdot ln[C \cdot FB1 \cdot (D \cdot F2T + E \cdot F2P)]\} \cdot FBN \cdot FBT$ $FB1 = \eta_{ST} \cdot \dot{m}$ $F2T = T_{in} - T_{out} - T_{out} \cdot ln(T_{in}/T_{out})$ $F2P = T_{out} \cdot ln(P_{in}/P_{out})$ $FBN = 1 + [(1 - 0.9)/(1 - \eta_{ST})]^3$ $FBT = 1 + 5 \cdot exp[(T_{in} - 1100)/(18.75)]$	*Frangopoulos* apud *Uche (2000a)*
Pump	$Z = A \cdot exp\{B \cdot ln[C \cdot \dot{m} \cdot D \cdot (P_{out} - P_{in})]\} \cdot FDN$ $FDN = 1 + [(1 - 0.8)/(1 - \eta_P)]^3$	*Frangopoulos* apud *Uche (2000a)*
Heat Exchangers	$Z = 12000 \cdot (A_{AREA}/100)^{0,6}$	*Frangopoulos* apud *Uche (2000a)*
Deaerator	$Z = R\$\ 1.300.000,00$	*Uchôa (2005)*
Desalination	$Z = 3054.A_d{}^{0,9751}$	*Rahimi (2015)*

Table 4. Steam Turbine and Pump Constants Costs. Adapted of *Frangopoulos* apud *Uche (2000a).*

Equipment	**Fluid**	**A**	**B**	**C**	**D**	**E**
Steam Turbine	Water	49964	0.2245	0.00987	9.971	1.852
Pump	Water	2024	0.2881	0.008574	7.225	- - - -

Based on these costs, the general equation for the cost rate ($\dot{Z}_i$, in *R$/s*), associated with the capital investment and the maintenance costs for each component, is obtained using Eq. (18), where the purchase equipment costs (Z_i) are shown in Table 3, maintenance factor (φ) is 1.05, n_{hours} are 5.7 hours, and the annual capital recovery factor (CRF) is shown in Eq. (19), where i = 0.6 is the rate and n_{years} are 25 years.

$$\dot{Z}_i = \frac{Z_i \cdot CRF \cdot \varphi}{n_{years} \cdot n_{hours} \cdot 3600} \tag{18}$$

$$CRF = \frac{i \cdot (1+i)^{n_{year}}}{(1+i)^{n_{year}} - 1} \tag{19}$$

As described by Faria (2014), thermoeconomic methodologies are divided into two groups according to the type of structure used to formulate the mathematical model that represents the cost formation process, one in relation to the physical structure and its flows and the other related to the productive structure and its flows. According to Faria (2014), the H&S model (Level IIb) offers the same level of complexity when compared to E^T & E^M (Level IIa), for example, but proposes a higher level of precision in the results. In order to calculate the monetary unit cost (c) of each internal flow and final products, cost equation balances are made in each subsystem. In Eq. (20), c_{out} and c_{in} are monetary unit cost of the flows at the outlet and the inlet of the subsystems (in R$/kJ), Y_{out} and Y_{in} represent the internal flows (in kW) at inlet and outlet of the subsystems respectively, which can be assessed by using any thermodynamic magnitude, such as, power (W), total exergy (E), entropy (S), enthalpy (H), etc; and Z represents the external hourly cost of the subsystem due to the capital, operation and maintenance cost of the equipment (in R$/s).

$$\sum(c_{out} \cdot Y_{out}) - \sum(c_{in} \cdot Y_{in}) = \dot{Z} \tag{20}$$

In the Figures 6, 7, 8 and 9 represent the productive diagram, according to H&S Model to MED and CSP with basic Rankine cycle, regenerative Rankine cycle, reheat Rankine cycle and reheat-regenerative Rankine cycle, respectively.

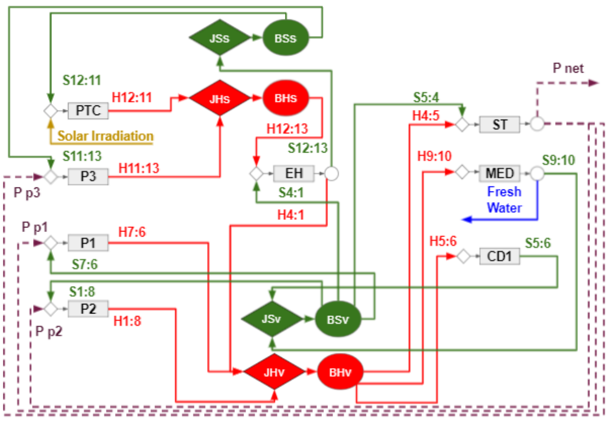


Figure 6. Productive diagram MED and CSP with basic Rankine cycle.

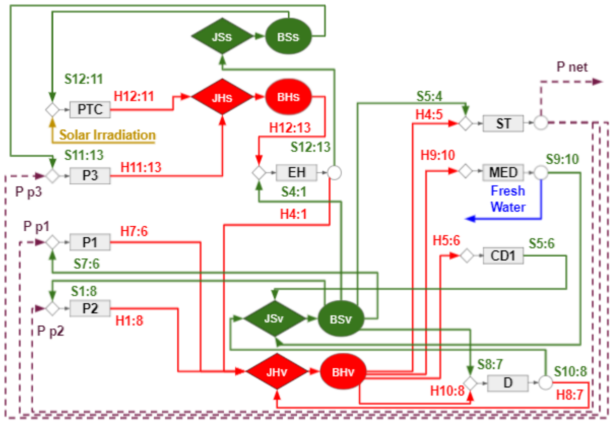


Figure 7. Productive diagram MED and CSP with regenerative Rankine cycle.

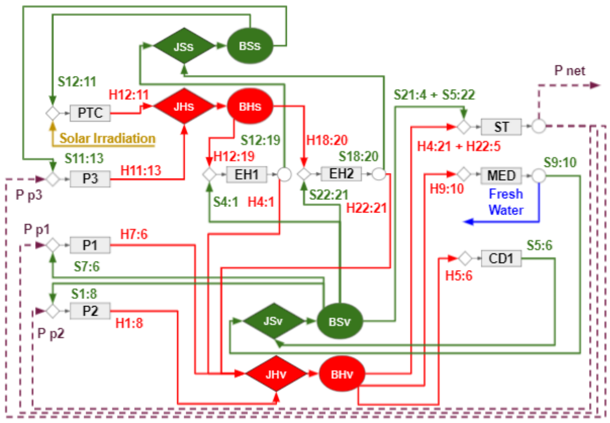


Figure 8. Productive diagram MED and CSP with reheat Rankine cycle.

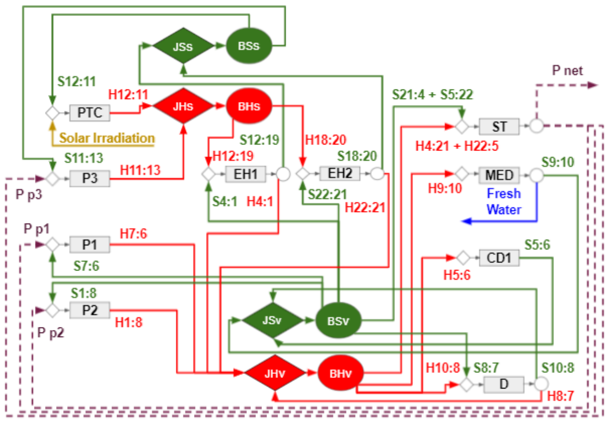


Figure 9. Productive diagram MED and CSP with reheat-regenerative Rankine cycle.

2.3 Optimization Model

For the optimization process through the G.A method, it was proposed to minimize the ratio between total hourly cost rate of each equipment ($\sum \dot{Z}_{Equipament}$) and the net power generated through an objective function observed in Eq. (21). This analysis was similarly adopted by Ribeiro (2017) for determining the optimal configuration of an organic Rankine cycle. Therefore, this process was performed in the Engineering Equation Solver (EES) software.

$$F_{Objective} = \frac{\sum \dot{Z}_{Equipament}}{W_{Liquid}} \quad (21)$$

Therefore, it became necessary to define 9 decision variables in order to elaborate the definition process and its variation limits, which can be seen in Table 5.

Table 5. Variables of decision.

Parameters	*Minimum Value*	*Maximum Value*
P_5	0.05 bar	1 bar
P_4	10 bar	80 bar
P_{22}	5 bar	10 bar

η_{Pump}	40 %	92 %
$\eta_{Turbine}$	40 %	92 %
w	20 %	50 %
y	1	40
$\Delta T_{superheat}$	10 °C	50 °C

Where P_5, P_4, and P_{22} are the pressure of condenser, high turbine and low turbine, respectively. The η_{Pump} and $\eta_{Turbine}$ are the pump and turbine efficiency, respectively. The w and y are the percentage of mass rate flow to desalination and the number of collectors solar in line, respectively, and $\Delta T_{superheat}$ is the difference between the outlet oil temperature in the collector solar and the inlet steam temperature in the turbine.

For the optimization parameters it was determined: Number of individuals equal to 16, number of generations equal to 128 and maximum mutation ratio equal to 0.2625.

3. RESULTS

According to the methodology adopted above, it obtained the results of the decision variables for the variation criteria presented in Table 5. Thus, through Table 6, it can observe the optimal values for minimizing the cost per produced power.

Table 6. Summary of results to variables of decision.

Parameters	***Rankine cycle with CSP (a)***	***Rankine cycle with CSP (b)***	***Rankine cycle with CSP (c)***	***Rankine cycle with CSP (d)***
P_5	0.08 bar	0.10 bar	0.16 bar	0.07 bar
P_4	42.95 bar	34.59 bar	66.31 bar	56.97 bar
P_{22}	-	-	7.25 bar	6.10 bar
η_{Pump}	77%	82%	71%	86%
$\eta_{Turbine}$	92%	91%	92%	92%
w	21%	21%	22%	20%
y	25	30	19	31
$\Delta T_{superheat}$	48.83 °C	18.86 °C	17.60 °C	10.67 °C

Thus, it was only possible to obtain these values through the convergence of the objective function. It can be observed in Figure 10 the convergence of the objective function according to the number of functions calls for each type of plant.

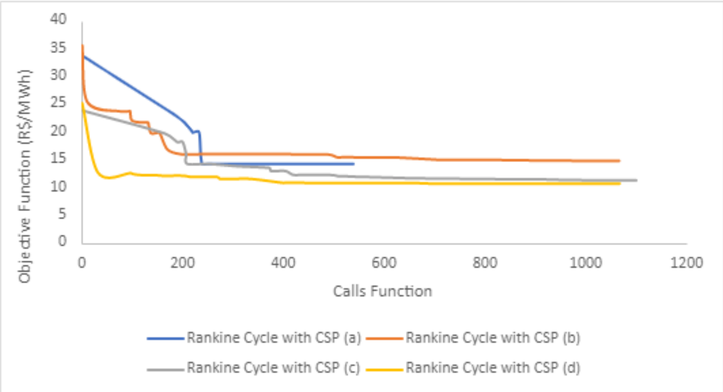
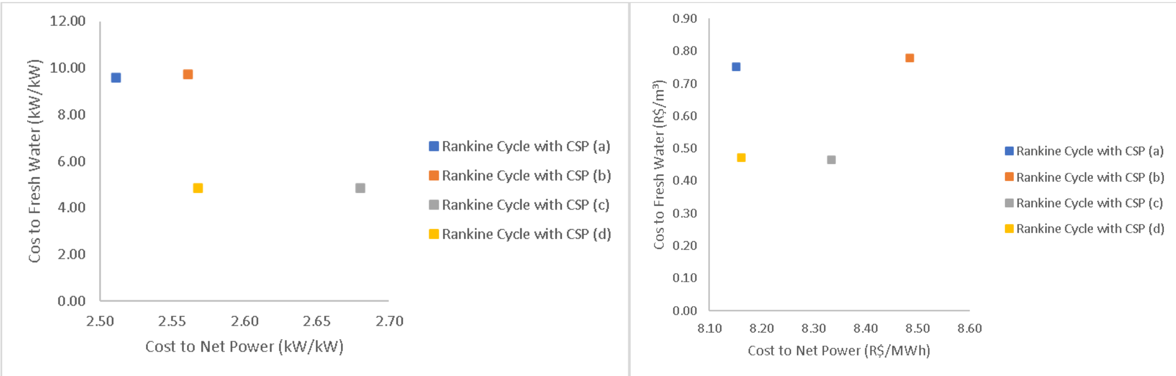


Figure 10. Graph of convergency of objectives functions to each set up.

It was observed through Table 7 and Figure 11 the values: of net power and total area of the parabolic collectors, the exergetic and monetary cost for desalinated water production and net power.

Table 7. Summary of results.

Analized Plants	*Net Power (MW)*	*Total Area of PTC (m²)*	**Cost to fresh water**		**Cost to net power**	
			Exergetic [kW/kW]	**Monetary [R$/m³]**	**Exergetic [kW/kW]**	**Monetary [R$/MWh]**
Rankine with CSP (a)	12.41	90,279	9.57	0.75	2.51	8.15
Rankine with CSP (b)	12.33	91,602	9.74	0.78	2.56	8.49
Rankine with CSP (c)	15.82	94,654	4.85	0.47	2.68	8.33
Rankine with CSP (d)	18.59	104,530	4.87	0.47	2.57	8.16



(f) (g)

Figure 11. Variation of costs for producing net power and desalinated water according to each Rankine cycle configuration (f) monetary and (g) exergetic.

It can be observed the all set up have an average value of 8.28 R$/MWh ± 0.14 R$/MWh. Moreover, observing for the production of desalinated water, the Rankine cycle (c) and (d) showed a lower monetary cost, which can be observed a value of 0.47 R$/m³, given that the Rankine cycle (b) showed a higher cost for the same production, with a value corresponding to 0.78 R$/m³.

In august 2021 the Brazilian tariff flag corresponded to red at level 2 with the value of 90.92 R$/MWh for electricity consumption and R$ 28.60 for every 5 m³ of water consumed. Thus, it can be seen through Figure 12 the gain through the production of electricity and desalinated water.

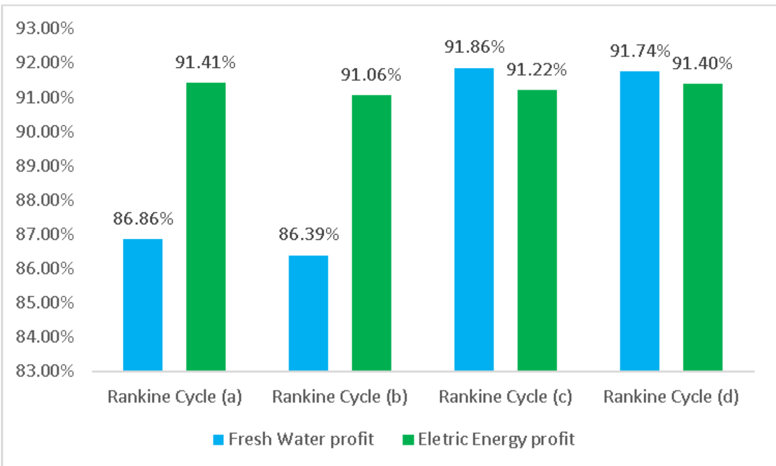


Figure 12. Fresh water and electric energy profit.

4. CONCLUSION

This study demonstrated the behavior of the costs of cogeneration for power generation and desalinated water as an application proposal in the city of São Mateus - ES. Note that the Rankine cycles (c) and (d) have a greater advantage in implementation, given the greater profit for the production of desalinated water. In relation to the production of electric energy, the 4 setups result in an average profit equivalent to 91.27% ± 0.14%. Finally, it becomes more advantageous to implement the MED and CSP with Rankine cycle (c) due to its higher profit to fresh water compared to the other cycles analyzed. Further studies will be developed to elaborate other possible configurations for cost analysis for the same production (net power and desalinated water).

5. REFERENCES

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