Analysis of the behavior of a parabolic trough collectors’ plant for weather conditions of Cartagena - Bolivar

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Abstract. Solar energy and concentration technologies, have gained importance in recent years due to their versatility and positive impact on the environment. Varios son las tecnologías que se pueden utilizar para generar electricidad, a partir de la irradiación solar, sin embargo, la tecnología de Colectores Cilíndrico Parabólico, recibe el reconocimiento por tener mayor desarrollo comercial. Before this panorama, this work analyzes the solar radiation potential of the city of Cartagena is located in Colombia with Elevation of 32 m, Latitude (10.57°), Longitude (-75.46), DNI 40.84 KWh/m²/day, DHI 2.26 KWh/m²/day, Average wind speed 4.5 m/s for the use of parabolic trough collector to generate electricity. To achieve the purpose of this work, a methodology is implemented for the characterization of this type of plants. In the initial stage, the requirements of the solar field are considered and configured. Followed by the stage of characterization of the thermal storage system, and configuration of the system. To later characterize the power cycle, an operating parameter to respond to the energy demand defined in this research. In the final part of this work, an analysis of operating parameters is proposed, in order to obtain improvements in the configuration of the proposed system. The results obtained allowed us to determine that for the evaluated conditions and the configuration of the determined plant, it can operate with the Therminol PV-1 fluid, a solar multiple of 1.7 and solar salt, as the storage system fluid.

1. Introduction
Due to the high cost of electricity, energy independence, and increased demand, solar energy became an emerging form of end-use energy choice. After wind power, it is the second-largest source of energy for electricity generation [1]. Solar energy is available in abundance across the globe and can be used for solar thermal power generation applications and electricity generation [2].

Currently, the use of solar technologies has diversified, for example, energy generated through solar concentration collectors. [3]. In particular, the Parabolic Trough Collector (PTC) is a concentration technology that has proven to be useful in medium to high-temperature applications [4]. PTC technology is more straightforward and more feasible compared to similar types of solar collectors [5]. Like the ones in the Central Tower [6] and collector Fresnel [7]. A PTSC is a line-focus concentrator which converts concentrated solar energy into high-temperature heat [8]. Depending on the application, temperatures up to 550 °C is achievable in these systems [9]. As shown in Figure 1, the PTSC assembly necessarily has several subsystems to be functionally operated.
The PTSC has a mirror or reflector curved in the shape of a parabola, which thus allows concentrating the sun's rays onto the focal line. The mirror is produced from different raw materials such as aluminum or low iron glass to lessen the absorption losses. The solar-weighted reflectivity of the mirror and its cost, durability, and abradable properties are essential factors during the production of the collector mirrors, after bending the mirror, a set of manufacturing processes such as silvering, protective coating, and gluing. In published scientific works, the following stand out: Bilal et al. 2018 [10] investigated the PTC system under transient weather conditions. A detailed study and its validation with the experimental data has been carried out. The thermal efficiency of the system is reported to be 76%. In a research study, Agagna et al. 2018 studied [11]. The parabolic trough system has been investigated by Bellos et al. 2020 [12]. Yuehong Bi [13] In this paper, the composition and operation strategy is elaborated in detail. Given the measured data of the solar energy and the cooling load demand of buildings, the intelligent matching design of the solar collector, absorption refrigeration chiller, and the three-phase accumulator is carried out. On this basis, the dynamic performance of the solar air conditioning system with the independent-developed PTC is analyzed. In general, there has been a lot of research related to PTCs that has allowed demonstrating the efficiency of these systems.

In view of the above and considering the global panorama, the main scientific contribution of this work consists of in the implementation of a calculation methodology for a Parabolic Cylindrical Collector plant integrated to a thermal storage system and a conventional Rankine cycle. Taking as a case study the climatic conditions of Cartagena - Bolivar. Research that has not been carried out by other authors, so this work represents an important basis for evaluating the potential of the solar resource for this region of the Country and starting point for other research.

2. Place Description

Cartagena is located in Colombia with Elevation of 32 m, Latitude (10.57°), Longitude (-75.46), DNI 40.84KWh/m2/day, DHI 2.26 KWh/m2/day, Ambient temperature 27.3°C, Average wind speed 4.5 m/s. Because of its geographical and astronomical position, it has a high potential for solar radiation. Table 1 shows the solar radiation available in Colombian regions:

| Region    | kW/m2/year |
|-----------|------------|
| Guajira   | 1980-2340  |
| Atlantic coast | 1260-2340  |
| Orinoquia | 1440-2160  |
| Amazonia  | 1440-1800  |
| Andina    | 1080-1620  |
3. Methodology

This section will present the stages implemented in this research work required to characterize the behavior of the PTC system. Figure 2 shows the calculation sequence defined in the methodology described in this study.

It is important to mention that the calculation sequence defined in Figure 2 allowed the definition of the equations and considerations necessary to characterize this type of system. From these, a System Advisor Model (SAM) analysis was developed to determine and analyze in an iterative way, the different calculations required to create the report proposed in this study.

3.1 Characteristics of the System

For this analysis, parabolic cylinder diagrams with Physical Model specifications were used in the SAM software. This allows the study of the geometry and properties of the system components to be represented using parameters from the manufacturers of these devices. Table 2 shows the Description of the analysis properties of the solar plant for the SAM simulation, and later in each subsection of this stage will be detailing the established configurations.

Table 2. Description of the solar plant's properties.

| Property                                           | Value               |
|----------------------------------------------------|---------------------|
| Nominal potential (MW)                             | 1                   |
| Number looping                                     | 3                   |
| Number total collector                             | 12                  |
| Extension collectors (m²)                          | 6 acres             |
| Solar multiple                                     | 1,7                 |
| Annual gross electricity production (MWh)          | 2,818,537           |
| Collector type                                     | Eurotrough ET-150   |
| Thermal oil                                        | Therminol VP1       |
| Storage type                                       | Indirect from two tanks |
| HTF storage                                        | Sola Sal r          |
| Rankine Cycle Performance                          | 0,358               |
| Overall plant performance                          | 0,89                |
3.2 Mathematical components

3.2.1. Solar field

For this study, the configuration (Solar Multiple(SM)) was used, for which SM is defined as the quotient between the thermal power produced by the solar field at the design point and the thermal energy required by the power block (Rankine Cycle), a multiple of 1.70 is selected [15].

\[ SM = \frac{Q_{\text{thermal, solar field}}}{Q_{\text{thermal, power block}}} \]

3.2.2. Configuration verification for PTCs

When verifying the sizing configuration in this section, it should be noted that the maximum performance of the Rankine (\(\eta_{\text{pot}}\)) of a solar thermodynamic power plant is from 38% [15], so.

\[ P = \frac{P_{\text{real}}}{\%\text{performance}} = \frac{0.648 MW'}{0.38} = 1.70734311 MW' \]

\(P_{\text{real}}\) thermal power consumed ; \(P_k\) efficient thermal capacity.

3.2.3. Increase in oil temperature per collector

To calculate the temperature increase in the oil under the conditions of analysis, it is determined from the thermal losses that will be obtained with the overall coefficient (\(U_{\text{labs}}\) W/m² °C specified in the manufacturer's data sheet and used in another essential study [16].

\[ U_{\text{labs}} = a + b(T_{\text{abs}} - T_{\text{amb}}) + c(T_{\text{abs}} - T_{\text{amb}})^2 \]  

The values of the coefficients \(a\), \(b\), and \(c\) of the equation are chosen for a working temperature in the range of 340°C as a reference for the next value of 342°C. The values of the coefficients are 2.8954; -0.0164 and 0.000065, respectively, according to the coefficient tables calculated by the Latin American solar platform for the Eurotrough [16].

\[ U_{\text{labs}} = 2.8954 - 0.0164(342 - 27.3) + 0.000065 (342 - 27.3)^2 \]

\[ U_{\text{labs}} = 4.1716 \frac{W}{m^2 \text{ abs }^\circ C} \]

Taking into account the dimensions of the collector's absorber tube, the thermal losses are calculated ( \(Q_{\text{loss}}\) ) in the collector whose average temperature is the same in the absorber tube (\(T_{\text{abs}}\)) is of the 342°C [16].

\[ Q_{\text{loss}} = U_{\text{labs}}A_{\text{abs}}(T_{\text{abs}} - T_{\text{amb}}) \]  

\[ A_{\text{abs}} = L.D.\pi \]  

\[ Q_{\text{loss}} = U_{\text{labs}}A_{\text{abs}}.32.65.(342 - 27.3) \]

\[ Q_{\text{loss}} = 4286.67 W \]

Incident solar energy is calculated (\(Q_{\text{sol}}\)) at the opening of the Eurotrough collector, taking into account the area of the collectors (\(A_c\), the direct irradiation (Identical design), the angle of incidence considering the installation and handling space is increased to K=17.80°).

The following equations are taken from [17].

\[ Q_{\text{sol}} = A_c \cdot I_{\text{design}} \cos(\theta) \]

\[ Q_{\text{sol}} = 817,5 \cdot (950) \cos(10) \]

\[ Q_{\text{sol}} = 386725,235991 \]
4. Results
In table 3, the configured and obtained values are collected to proceed with the analysis of the expected results.

Table 3. Values obtained in the configuration and simulation of SAM.

| Parameter                                      | Value                          |
|------------------------------------------------|--------------------------------|
| $T_{\text{amb}}$ ($^\circ$C)                  | 27,30                          |
| SM                                             | 1.70 Solar Múltiple            |
| $I_{\text{design}}$ (W/m²)                    | 950                            |
| $T_{\text{in}}$ ($^\circ$C)                    | 293                            |
| $T_{\text{out}}$ ($^\circ$C)                   | 391                            |
| $T_{\text{abs,Tmed}}$ ($^\circ$C)              | 342 Theoretical average value  |
| N. Reynolds                                    | $1.37 \times 10^6$             |
| $V_{\text{max}}$ (m/s)                        | 4,96554 (Fluid velocity in the solar loop) |
| $V_{\text{min}}$ (m/s)                        | 0.35 (Fluid velocity in the solar loop) |
| $\dot{m}_{\text{max}}$ (kg/s)                 | 12kg/s (Mass flow in the solar field) |
| $\dot{m}_{\text{min}}$ (kg/s)                 | 1kg/s (Mass flow in the solar field) |
| $\Delta P$ (Pa)                               | 15767.18 (Pressure drop)       |
| $S_t$ (m²)                                     | 33.18 $\times 10^{-4}$ (Section of the pipe) |
| $\dot{m}_{\text{max}}$ (kg/s)                 | 12.85kg/s (notional value)     |
| $\dot{m}_{\text{min}}$ (kg/s)                 | 0.95kg/s (notional value)      |
| $N_{\text{Reynolds}}$                         | 3                              |
| $A_c$ (m²)                                     | 817.50 (opening reflective area) |
| $P_R$ (MWt)                                    | 1,701 (efficient thermal capacity) |
| $P_{\text{L.real}}$ (MWt)                     | 0.64 (Actual thermal output)    |
| $U_{\text{L.abs}}$                             | 4.17 (overall rate)            |
| $A_{\text{abs}}$ (m²)                         | 32.65 8 (Absorber tube area)   |
| $Q_{\text{L.toil}}$ (W)                       | 4286.67 (thermal losses)       |
| $Q_{\text{sol}}$ (W)                          | 386725.23 (Incident solar energy) |
| $Q_{\text{Useful}}$ (W)                       | 327 124.89 (Collector power)   |
| $T_{\text{oil}}$ ($^\circ$C)                  | 10.76 (theoretical value of the thermal increase of the oil) |
| $\eta_{\text{solar}}$ (%)                     | 76 Theoretical value of the solar field yield) |

4.1. Analysis of plant energy production
The first data provided by SAM when carrying out the simulation is the analysis of annual net electricity production for the 25-year life of the plant, which we will compare from the following table 4:

Table 4. Comparison of obtained vs. theoretical results.

| Parameter            | Value         |
|----------------------|---------------|
| Power rating SAM     | 0.671MW       |
| Power rating Req     | 0.648MW       |
| Annual Energy SAM    | 2 818 537 KWh |
| Energía anual Req    | 2 698 968 KWh |
| Net power with a safety factor | 108 KW |
| Extra energy produced by SAM | 119 569 KWh |

4.2. Theoretical calculations to verify power output
The peak consumption value for the case study defined in this work is 224914 KWh in the month of August. Considering the operating parameters, the nominal power required to produce the plant is obtained:
1. To have an estimate of the energy that should be produced with this peak value:

\[
\frac{224914\ kW}{h} \left( \frac{1\ month}{26\ days} \right) \left( \frac{1\ day}{16\ h} \right) = 540\ kW
\]

2. As the value obtained can fluctuate to a higher or lower value, it has been considered a safety factor of 1.2. This will allow over-dimensioning the energy production of the plant and make use of the storage system for when the system requires it.

\[
540\ kW \times 1.2 = 648\ kW = 0.648\ MW
\]

This means that 108 KW is protected from the real peak value, which is why the solar plant is simulated with 1MW and not with 0.648MW.

The results of the annual production with SAM should be considered that the dimensioning of the installed power depends mainly on the limitations of the available area (9 acres) and critical parameters that have been assumed to affect the optimal performance that can be achieved by the plant. Figure 3. Even so, the result obtained satisfies the demand for the peak value generated by the needs of the Universidad Technological de Bolivar.

![Figure 3. Annual energy production result SAM.](image)

In figure 3 you can see that a value of energy higher than the nominal value of the power is obtained, and although it was estimated a drastic degradation in the performance of the plant of 20\% per year, it is obtained for the final year of estimated useful life 2750000 KWh.

In Figure 4, and can be seen that each month is obtained a value ranging from 224914Kwh, which corresponds to the maximum value consumed by the university.
Figure 4 shows that in the first months approximately 121224KWh is produced in addition to the required peak value of 224914Kwh. This monthly surplus can be stored to supply the months detected by the program with less production, and this is possible because the surplus energy that is stored in the tanks can be used later months as if it were seasonal thermal energy storage, where commonly stores energy in the summer to supply during the winter.

Conclusions
At the end of this work, the results obtained were analyzed. It was concluded that the generation of electric energy using the installation of the parabolic cylinders, which corresponds to a thermoelectric plant of heliothermic technologies, has been viable due to the fact that 2,818,537 kWh are produced per year, which corresponds to 1MW of nominal power against the demand of required energy that is 0.648MW. This is mainly because there is a suitable location where radiation values are sufficiently high. There are no seasonal changes, allowing for much more stable solar irradiation than in other countries where these solar plants have been implemented.

There are several options that can be implemented in this type of system, in order to obtain improvements in the performance of this type of plant. As a result of a sensitivity analysis of project parameters and operation of the system proposed in this work. It was possible to determine that with the increase in the area available for the installation, going from 6 acres to 9 acres and using a solar multiple of 1.7, it allows to adequately guarantee the energy available in the thermal storage system, to guarantee autonomy system for 6 hours.

From the analysis carried out in this work, it was also possible to determine for this parameter analysis, which for the different heat transfer fluids of the solar field. Therminol PV-1 allows to obtain the best performances of the proposed system, in relation to other fluids used, such as: Dowtherm, Caloria HT 43 and Therminol 59.

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