

Article

Evaluation of Energy Efficiency and the Reduction of Atmospheric Emissions by Generating Electricity from a Solar Thermal Power Generation Plant

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Abstract: The increase of renewable energy generation to change the productivity of a country and electrify isolated sectors are some of the priorities that several governments have imposed in the medium term. Research centers are looking for new technologies to optimize the use of renewable energies and incorporate them into hybrid generation systems. In the present work, the modeling of a solar thermal energy generation plant is being carried out. The climatic data used belong to two coastal cities and one island of Ecuador. The contribution of this work is to simulate a complete model of SCF and PCS, in which the variables of outlet temperature and oil flow are involved at the same time. Previously investigations use only outlet temperature for evaluating power plants. The model of the solar thermal plant is composed of a field of solar collectors, a storage tank, and an energy conversion system. As a result, we obtain a model of a thermosolar plant that will allow us to make decisions when considering the incorporation of micronetworks in systems isolated from the electrical network. The use of thermosolar technology allows the reduction in the risk of spills by the transport of fossil fuels in ships. The study of the CO₂ emission factor in Ecuador from 2011 to 2018 is also carried out.

Keywords: electric generation; solar collectors; renewable energies; autonomous systems

1. Introduction

One of the main challenges to be reversed according to global development indicators is the high concentration of greenhouse gases (GHG) due to the use of fossil fuels in electricity generation applications and industrial processes [1,2]. One of the means to achieve a reduction in GHGs is the use of technologies to convert solar energy into electricity. Among the main ones, we have photovoltaic (PV) [3] and concentrating solar thermal (CST). The most used solar collectors are shown in [4,5] such as flat-plate, parabolic compound, evacuated tube (heating of fluids to temperatures up to 200 °C; parabolic trough, Fresnel lens, parabolic dish, and heliostat fields (heating of fluids to temperatures up to 400 °C are the main technologies used for concentrating solar energy. In reference [6], the authors present free applications that allow the design of solar fields.

This work focuses on parabolic trough solar thermal power plants, which consist of a Solar Collector Field (SCF) [7], thermal energy storage (TES) [8], Power Conversion System (PCS) [9] and auxiliary elements such as pumps, pipes, and valves. Solar collectors use solar radiation to heat fluids such as oil or water. Thermal energy is used for heating or the production of steam for electric generators. Works such as [10,11] describe the use of solar thermal plants for electricity generation.

For heating or the production of steam for electric generators, thermal energy is used. The main goal of a parabolic trough solar field is to collect the maximum solar energy to produce as much

electrical power as possible [12]. To achieve the best performance of the plant, electrical power depends on the outlet temperature and the oil flow. The controls applied for these plants must be able to maintain the plant's performance on days when solar irradiance is low. Xiufan and Yiguo employ a mathematical model of a PTC based on HTF energy balance, absorber tube, and glass envelope [13]. Linrui et al. incorporate the heat loss of the absorber based on the energy balance [14]. Research like Camacho and Gallego [15] propose changes in the outlet temperature set point according to the value of the solar irradiance, but the oil flow is not covered by the proposed model.

The novelty of this work is to simulate a complete model of SCF and PCS, in which the variables of outlet temperature and oil flow are involved. The simulation will be carried out by the TRNSYS software [16]. At the same time, Matlab software will be used to show the validations of the models based on the first principles of SCF and PCS operation; which was the case of [15].

A work similar to the current studio with TRNSYS is presented in reference [17]. The authors use TRNSYS software to evaluate different options of integration of the set of solar collectors, the needs of heating and hot water for a family dwelling are calculated.

Performing tests prior to the installation of the systems prevent over-sizing and under-sizing. In the specialized literature, modeling and simulation programs can be found, among the main ones and with a better answer in solving these problems are MATLAB [18] and Transient Systems Solution Program (TRNSYS) [17,19].

For the modeling and simulation of solar collector fields (SCF), energy production and simulation models based on mathematical equations are used that govern the components with respect to the principle of operation of the same [20]. Using data in real-time allows developing strategies for the design and control of plants.

On the other hand, this study aims to estimate how many GHG emissions will be avoided by fuel consumption and to evaluate the emissions that the solar thermal plant produces due to its manufacture and maintenance operations. Chengzhou et al. conducted a study on the typical amount of pollutant emissions into the environment directly for each power generation technology [21]. To this end, a study of the CO₂ emission factor in Ecuador is proposed, which is where the plant will be implemented in different coastal cities.

The objective of this paper is the modeling of solar thermal power generation plant for the supply of electrical energy. This document is structured as follows. After the introduction, the modeling of the solar collector field is presented in Section 2. Section 3 shows the testing of the solar thermal power generation plant for three plants. In Section 4, the study of emission factors in Ecuador is proposed. Finally, the results and conclusions of the document are exposed.

2. Materials and Methods

Figure 1 shows the components that make up a solar generating plant. These are solar collector field, storage tank, steam generation, steam turbine, and electrical generator. In the solar collector field (SCF), solar irradiance heats the fluid circulating through the SCF causing it to reach temperatures in excess of 200 °C. Thermal energy is accumulated in the storage tank. The thermal energy is then used by a steam generator, which produces a steam pressure capable of moving a turbine. The mechanical power of the turbine turns the electric generator sending the electric power to the micro-grid. The set of steam systems and electric generators is called Power Conversion System (PCS). The condensate produced in the PCS is treated and returned to the steam generator. The set of SCF, storage tanks, and PCS systems are called Distributed Collector Systems (DCSs) [22,23].

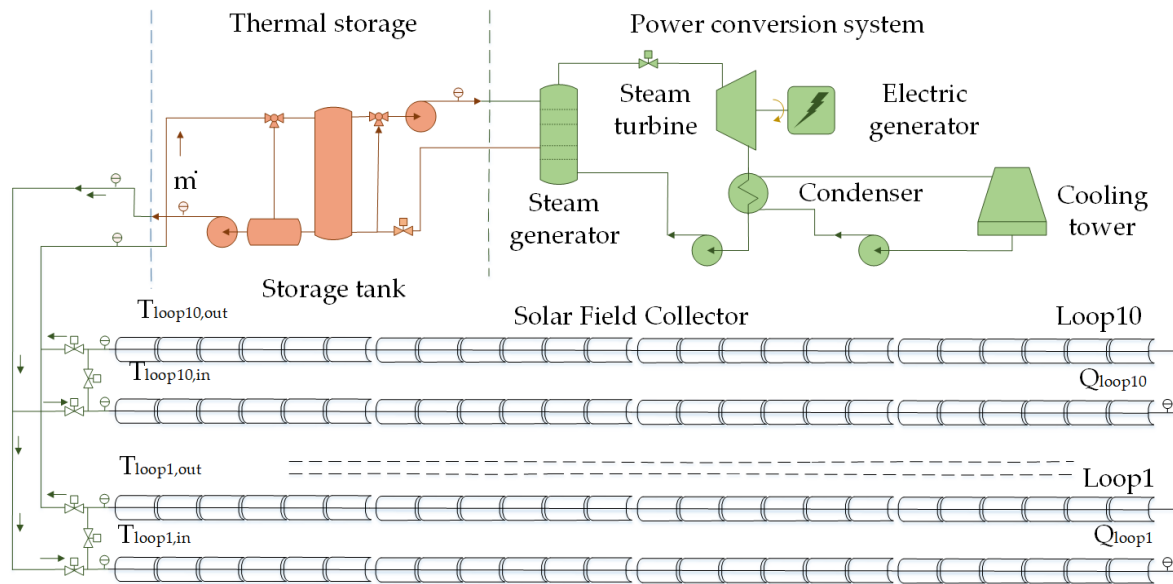


Figure 1. Solar thermal power generation plant.

Solar thermal power generation plants are one of the most used renewable energy technologies in recent years [24,25] and have contributed significantly to the electrification of several countries worldwide.

Next, the SCF and PCS models will be described with their basic principles and foundations, such as the energy balance.

2.1. Solar Collector Field

In this section, the mathematical models based on differential equations of a parabolic trough collector loop are presented. The model of the whole field is described as the placement of several parabolic collector loops. The model of distributed parameters was tested and validated in studies such as [26], which are currently used in research papers ratifying its applicability [25,27,28].

Parameter Model

Each SCF loop has four sectors connected in series; the sectors contain 12 collector modules. The SCF has a total area of 2635.2 m² that receives solar irradiance in the absorber tubes [29]. In Figure 2, the distribution of the collectors is shown. Equation (1) describes the variation in internal plant energy, which provides the evolution of the outlet temperature, $T_{loop,out}(t)$. As can be seen, the outlet temperature of the loop depends on several inputs, the manipulated one, $Q_{loop}(t)$ is the volumetric flow, and the other ones act as disturbances: $T_{loop,in}(t)$ is the inlet temperature, $T_a(t)$ is the ambient temperature, $T_m(t)$ is the mean fluid temperature (see Equation (2)) and $I(t)$ is the solar irradiance. The equations modeling the dynamics of the outlet temperature of the loops are

$$\rho C_p A_{cs} \frac{\partial T_{loop,out}(t)}{\partial t} = I K_{opt} n_o G - \frac{\rho}{C_f} C_p Q_{loop}(t) \frac{T_{loop,out}(t) - T_{loop,in}(t - d_{tout-tin})}{L_{eq}} - H_l \frac{T_m(t) - T_a(t)}{L_{eq}} \quad (1)$$

$$T_m(t) = \frac{T_{loop,out}(t) + T_{loop,in}(t - d_{tout-tin})}{2} \quad (2)$$

where ρ is the fluid density and C_p is the specific heat capacity depending on the temperature in the fluid. Works such as [30] and [31] provide data on the thermal transfer fluid or HTF (Heat Transfer Fluid), which is Santotherm-55. This oil circulates through the collector system. Santotherm-55 is capable of reaching 305 °C without degrading. A_{cs} is the collector tube's cross area, L_{eq} is the length of the equivalent collector tube, H_l is the thermal losses coefficient expressed by (3), m primary circuit

mass flow rate and Δh increased enthalpy. K_{opt} is the optical efficiency, n_o is the geometric efficiency, G collector aperture, $d_{out-tin}$ is the delay between the outlet temperature and the inlet temperature, and C_f is a conversion factor to calculate the mass flow rate inside this hypothetical equivalent collector tube. It takes into account the number of parallel collectors in each loop-row, n_p , number of serial tubes in each collector, n_t , and $\text{kg}\cdot\text{h}^{-1}$ conversion.

$$-H_l = \frac{\dot{m} \cdot \Delta h}{\frac{T_{loop,out} + T_{loop,in}}{2} - T_a} \quad (3)$$

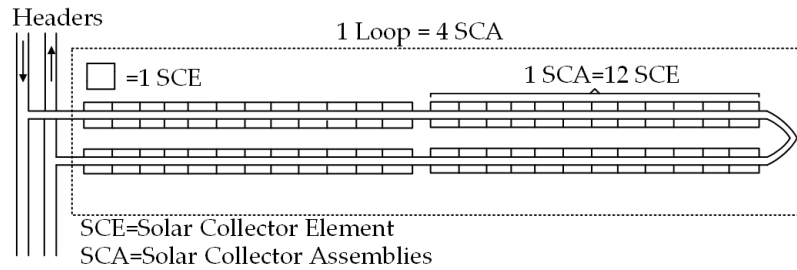


Figure 2. Distribution of collectors in the field.

2.2. PCS Model

As explained in the introduction, the PCS uses the high temperature coming from the storage tank to generate steam. The steam pressure spins the turbine which is coupled to an electric generator. This energy can be used in isolated systems or fed into the grid. The thermal energy W_t model is given by $P(T_{SCF,out})$ is calculated by the simplified model of the solar field in Equation (4) CM Cirre [32].

$$P(T_{SCF,out}) = IK_{opt}n_oG - \frac{H_1}{L_{eq}}(T_{SCF,out}, T_{SCF,in}, T_a)L_{eq}n_l \quad (4)$$

where, H_1 is the linear function of thermal losses. The investigation of CM Cirre [32] was to make several tests with different flows and inlet temperature, outlet temperature, and ambient temperature. With the tests, the linear regression is obtained (5).

$$H_1 = 1970 \left(\frac{T_{loop,out} + T_{loop,in}}{2} - T_a \right) - 34,651 \quad (5)$$

To convert the thermal energy W_t into electrical energy W_e , the maximum efficiencies of the complete DCS set formed by the SCF, the storage system and the PCS are used. Therefore, to perform the conversion, the system efficiency values found by CM Cirre [32] are used. Thermal storage efficiency chosen is $\bar{\eta}_{alm} = 0.98$ and the thermal into electric power conversion is $\bar{\eta}_{PCS} = 0.22$. The estimated energy that can be provided by the DCS is shown by Equation (6).

$$P(T_{SCF,out}) = IK_{opt}n_oG - H_1n_l\bar{\eta}_{alm}\bar{\eta}_{PCS} \quad (6)$$

In Table 1, PCS efficiencies are presented according to the tests carried out in years of operation.

Table 1. Power distribution at the Power Conversion System (PCS).

Property	Quantity
Net electrical power	500 kW
Parasites	77 kW
Gross electrical power	577 kW
Gross efficiency	$\eta_{\text{gross}} = 19.13\%$
Oil thermal power	$P_{\text{HTF}} = 3016 \text{ kW}$
Thermal losses	$L_{\text{PCS}} = 259 \text{ kW}$
Refrigeration losses	$L_{\text{rs}} = 3016 \text{ kW}$

3. Testing of the Solar Thermal Power Generation Plant

In this section, the solar collector field model is implemented through the TRNSYS program. TRNSYS has a specialized library with solar collector models, the storage tank, and the power conversion system. In Figure 3 is shown the scheme of the devices used for the simulation of the SCF. The field tests are carried out using the data provided by the TRNSYS, which contains solar irradiance, incidence angles, and the ambient temperature of several locations in Ecuador.

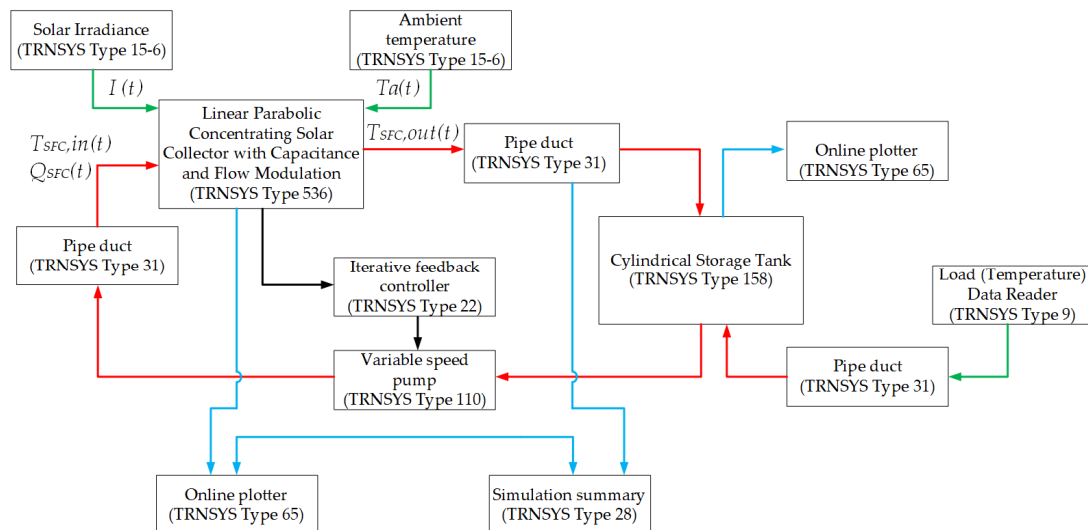
**Figure 3.** Model of Solar Collector Field (SCF) in Transient Systems Solution Program (TRNSYS).

Table 2 shows the values used for the dimensioning of the solar collector field, the storage tank, and the capacity of the power conversion system (the steam turbine and the electric generator).

To verify the correct functioning of the elements of the solar field, these elements are compared with a model based on the differential equations presented above and the model provided by TRNSYS Type 536.

The parabolic concentrator Type 536 is modeled on the theoretical equation developed in Solar Thermal Process Engineering [12,17]. With the presence of flow, the temperature of the fluid at the collector outlet is expressed by Equation (7).

$$\frac{\partial T_{\text{loop,out}}(t)}{\partial t} = T_{\text{loop,in}}(t) + \frac{A_{\text{cs}}(IK_{\text{opt}} - H_l(T_m(t) - T_a(t)))}{\rho C_p Q_{\text{loop}}(t)} \quad (7)$$

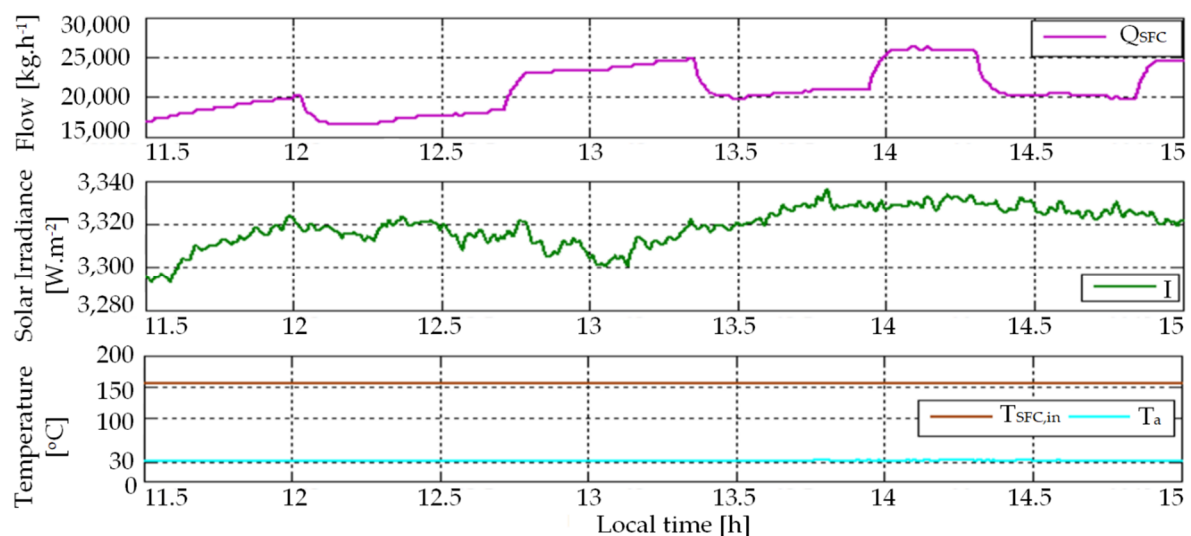
Table 2. Design parameters for solar power.

Property	Quantity	Unit
Collector Field		
Collector type	PTC	-
Parabolic width	1.83	m
Collector length	3.05	m
No. of collector	480	-
No. of loop	10	-
Total mirror area	2635	m ²
Mirror reflectivity	0.78	-
Storage Tank		
Type	Cylindrical	
Tank volume	115	m ³
Tank height	11.2	m
Tank loss coefficient	0.69	W·m ⁻² ·K ⁻¹
Power Block		
Electric generator output	0.5	MW _e
Turbine capacity	0.5	MW

The inputs are the same as those presented in Equations (1) and (2). However, for Equation (6), the entry temperature delay to the collector is not included.

For the validation of the TRNSYS model, it was necessary a Simulink/Matlab model for the evolution of the outlet temperature (dynamic model), $T_{loop,out}(t)$ represented by Equation (1). For the input data, the tests of CM Cirre's work [32] on control of a distributed solar collector field are replicated. For the tests of both models, the delay of the $T_{loop,in}(t)$ was discarded when there was a change of temperature.

In Figure 4, the input values are presented in the solar field for a sunny day, without clouds and in the summertime. Samples were taken from 11:50 to 15:00. The inlet fluid temperature ($T_{SCF,in}$) at the collector field remains constant at 153 °C. The ambient temperature T_a ranges from 30 °C to 32 °C. The solar irradiance I shows a minimum value of 867.19 W·m⁻² at 10:00 and a maximum value of 940 W·m⁻² at 14:38. The oil inflow flow (Q_{SCF}) at the collector field is provided by a controller with minimum values of 15,800 kg·h⁻¹ and a maximum of 25,000 kg·h⁻¹.

**Figure 4.** Simulated disturbances. The figure was changed.

In Figure 5, the results of the solar field output temperatures are presented using the differential equations with respect to the response given by the set of elements offered by the TRNSYS software. As a result, it is possible to observe that the TRNSYS model is suitable for the tests that will be carried out next with the thermal storage system and the power conversion system.

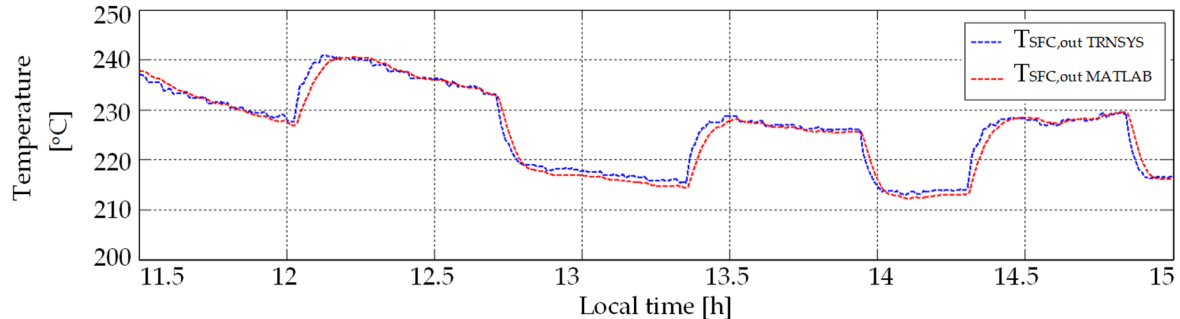


Figure 5. Solar field model validation.

3.1. Distributed Collector System

The complete system comprising the collector field, temperature storage, and power conversion system is shown in Figure 6, once the temperature is obtained through the collector field through the SCF estimated at 280 °C as the working temperature. It is necessary to analyze the performance of the thermal energy storage (TES) system.

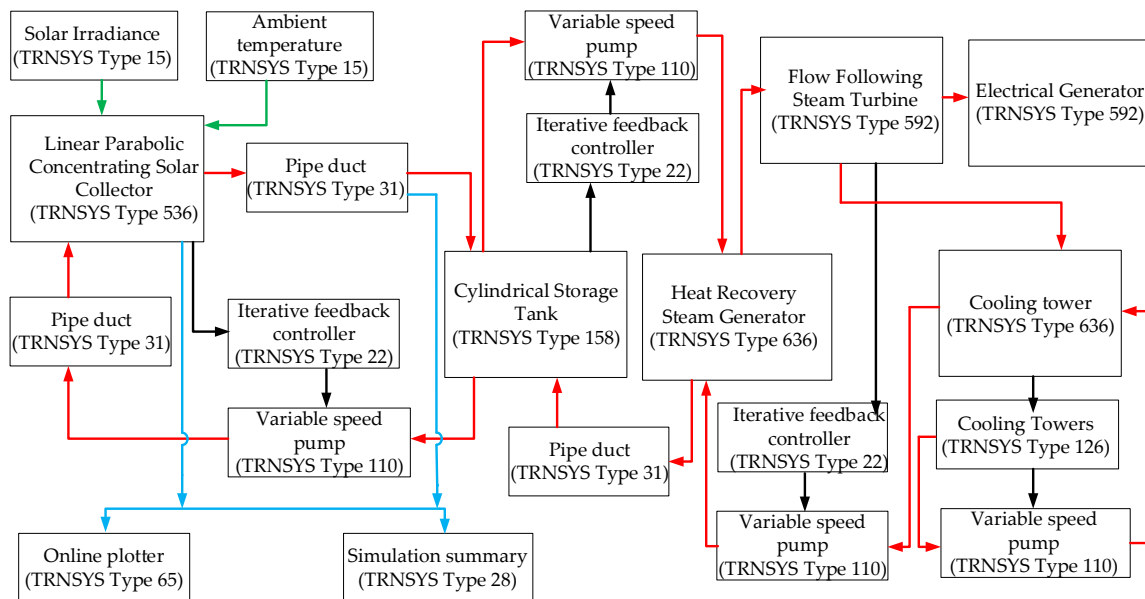


Figure 6. Model of the distributed collector system.

The stratified tank is divided into ten segments for analysis, in which, the highest temperature is in the upper part in the segment called “Top segment” and the minimum temperature in the lower part in the “Bottom segment”. From the Top segment, the fluid with the working temperature is driven to the steam generation system. In the steam generator, the produced steam reaches a pressure of 25 bar in order for the turbine can reach the working power of 500 kW. Input pressures for the tests are assigned by a controller that assesses the load.

The Type 22 Iterative Feedback Controller is designed to maintain the setpoints for temperature, oil and pressure flow. The iterative feedback controller tracks the tracking error $x_k (x_k = y - y_{set})$ with the secant method. Where x_k is the tracking error, y is a controlled variable and y_{set} is the set-point.

The secant method [33,34] calculates output signal $f(x_k)$ of a controller for minimizing tracking error. The method is defined by the recurrence Equation (8):

$$x_{k+1} = x_k - \frac{f(x_k)}{f(x_k) - f(x_{k-1})} (x_k - x_{k-1}) \quad (k = 1, 2, \dots) \quad (8)$$

where x_{k+1} is the root approximation of $f(x) = 0$, x_0, x_1 are the initial values of the secant method. In numerical analysis, the secant method is a root-finding algorithm that uses a succession of roots of secant lines to better approximate a root of a function $f(x)$.

According to the operating principles of the steam system, it is necessary to enter the thermodynamic variables; in Table 3, these variables are presented. Through the pressure and temperature of the steam, it is possible to find the specific enthalpy and vapor volume values through tables given by manufacturers specialized in steam systems.

Table 3. Values implemented in the steam system.

Property	Quantity	Unit
Steam enthalpy	25,000	$\text{kJ}\cdot\text{kg}^{-1}$
Steam pressure	25	bar
Steam exhaust pressure	16	bar
Steam mass flowrate	36,000	$\text{kJ}\cdot\text{kg}^{-1}$
Steam temperature	280	$^{\circ}\text{C}$
Pinch point temperature difference	7	$^{\circ}\text{C}$

In Figure 7, the input values are presented in the solar field for a sunny day, without clouds and in the summertime. Samples have been taken from 09:00 to 15:30. The fluid inlet temperature ($T_{\text{SCF,in}}$) at the collector field remains constant at 186.3°C . The ambient temperature T_a ranges from 30°C to 32°C .

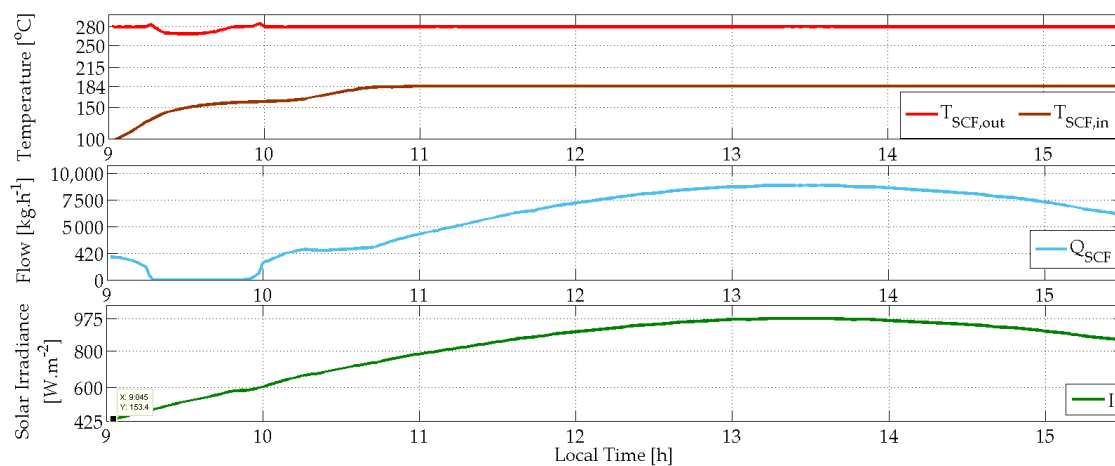


Figure 7. Results of the parabolic collector field.

The solar irradiance I shows a minimum value of $421.9 \text{ W}\cdot\text{m}^{-2}$ at 09:00 and a maximum value of $975 \text{ W}\cdot\text{m}^{-2}$ at 13:38. The input flow (Q_{SCF}) of the oil to the collector field is provided by the setpoint delivered by a controller with minimum values of $3600 \text{ kg}\cdot\text{h}^{-1}$ and maximum of $9832.8 \text{ kg}\cdot\text{h}^{-1}$. As can be seen, the flow of the pump from the collector field for a sunny day follows solar irradiance. ($T_{\text{SCF,out}}$) shows the temperature at the outlet of the collector field with a maximum value of 280°C .

Figure 8 corresponds to a loading operation in the storage tank, in which the HTF is heated in the collector field and enters the upper part of the tank. Due to the stratification in the tank, there are different temperatures. The oil volumes are significantly different. As the thermocouples are placed at intervals, the temperature changes are very pronounced.

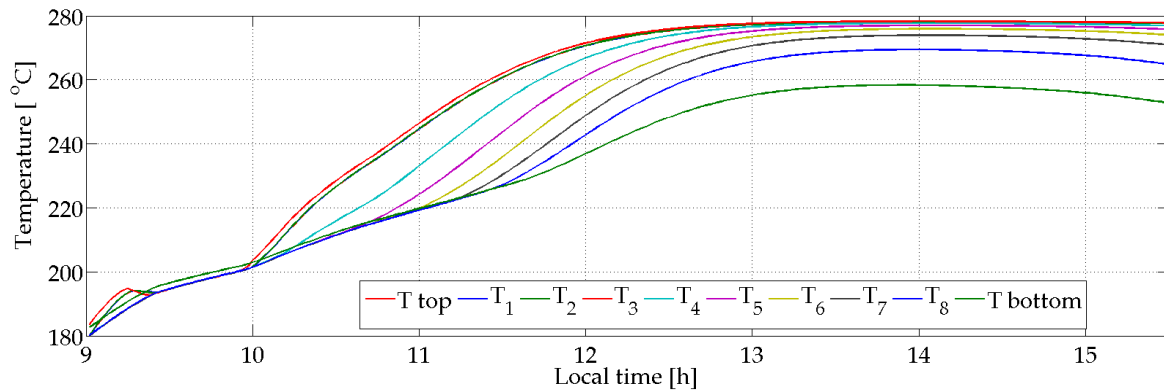


Figure 8. Evolution of the simulated oil temperatures during an experiment.

When the steam turbine is working the values of the inlet temperature to the power conversion system and its respective output are shown in Figure 9. The input temperature ($T_{PCS,in}$) has a minimum value of 180 °C and reaches 280 °C. This temperature is provided by the storage tank.

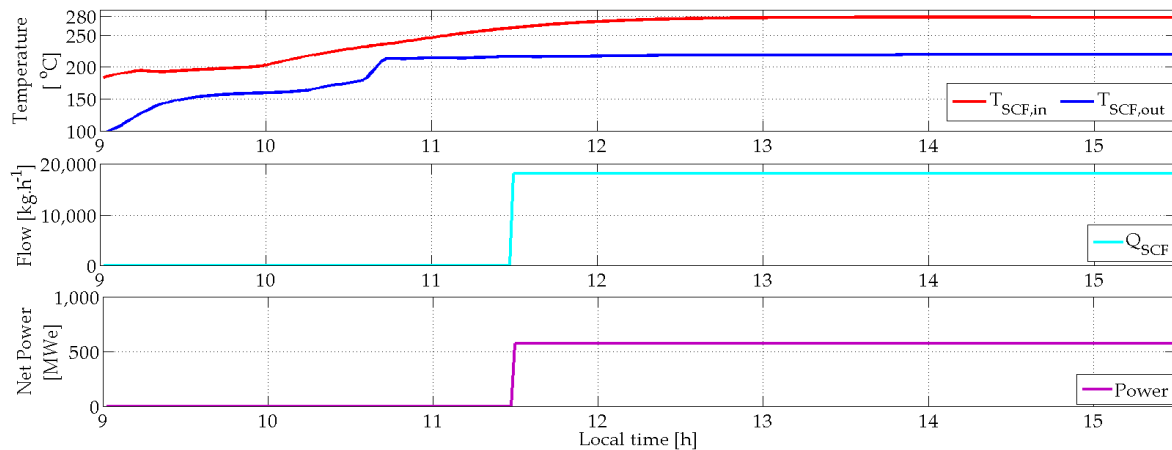


Figure 9. Input and output temperatures, workflow and power delivered by the Distributed Collector Systems (DCS).

The outlet temperature ($T_{PCS,out}$) has a minimum value and 99 °C and reaches 220 °C, the temperature ($T_{PCS,out}$) becomes the inlet temperature of the storage tank. As it is possible to appreciate, the temperature ($T_{PCS,out}$) presents a linear behavior, starting at 10:45 due to the continuous consumption of the steam turbine.

In the experiment that will be carried out next, it will be seen how the operation of the turbine depends on several factors such as weather conditions and electricity consumption, which makes necessary other types of controls that interpret the requirements of the work during a whole day.

The steam flow (Q_{PCS}) works at a value of 5277.8 W and the electrical power obtained by the generator (Power) reaches the value of 500 kW. The presented experiment is considered as the ideal for a DCS where it can work optimally.

3.2. Performance of the Plant

The results focus on the performance of the plant in different meteorological parameters of the three selected cities of the coast of Ecuador that are in different latitudes. The three selected sites are Guayaquil, (latitude 2.16° S and longitude 79.9° W), Manta (latitude 0.97° S and longitude 80.7° W) and San Cristóbal (latitude 0.87° S and longitude 89.44° W). As a sample, results of 7 days are taken to present the performance of the plant in winter (from 8 to 14 February) and in summer (from 13 to

19 July). Ecuador has two stations, Figure 10 shows the ambient temperature and solar irradiance recorded in the winter (December to May) and summer (June to November) periods.

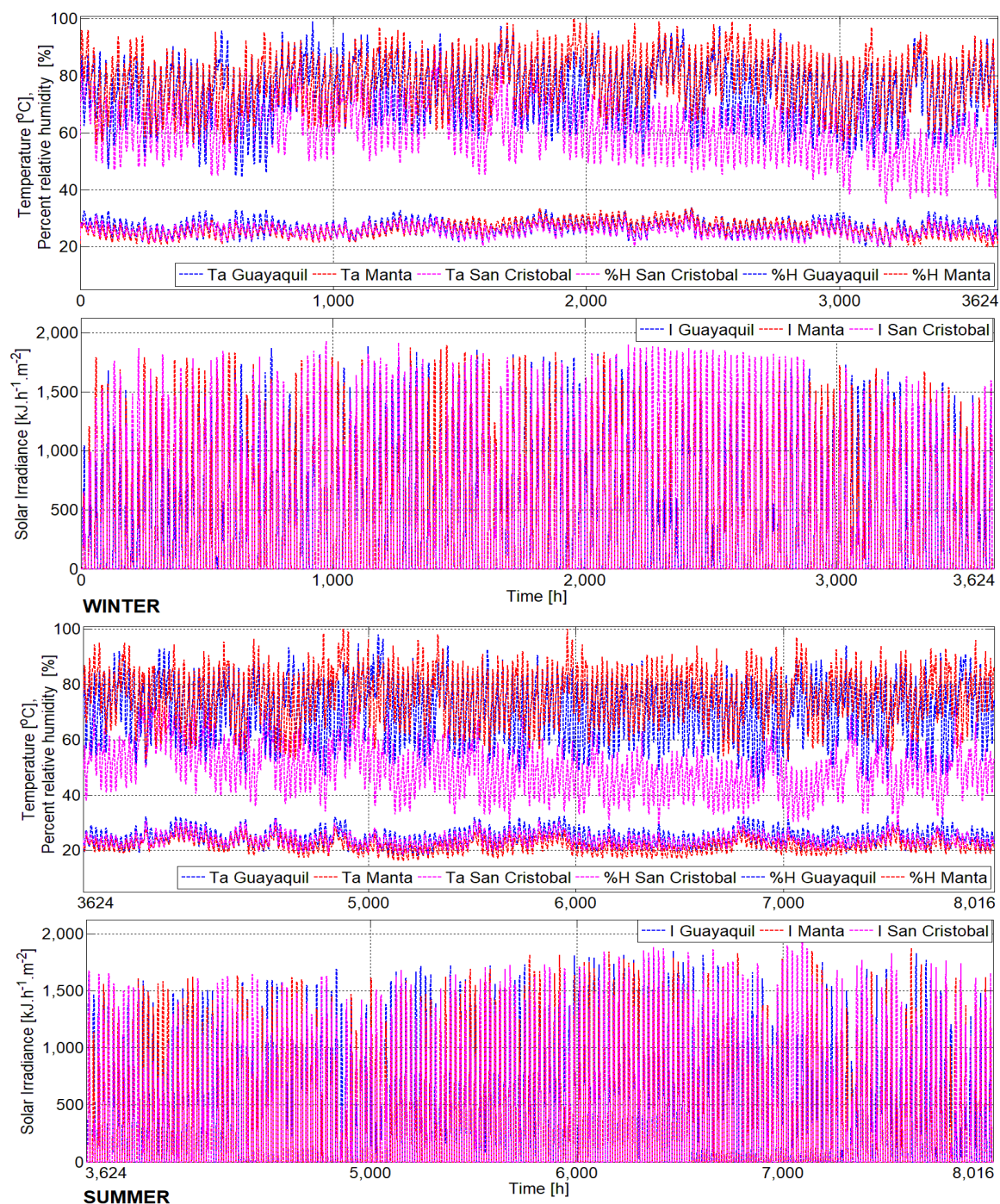


Figure 10. Solar irradiance in three selected sites of Ecuador from summer and winter.

The test for the proposed model was carried out with climatological data provided by the TRNSYS software for one year. As a characteristic of the evaluated cities, the average annual ambient temperature and annual maximum solar irradiance recorded are presented. The average ambient temperature is 25.7 °C for Guayaquil, 24.8 °C for Manta and 23.9 °C for San Cristóbal. The maximum recorded solar irradiance is 1046.8 W·m⁻² for Guayaquil, 1046.6 W·m⁻² for Manta and 1074.9 W·m⁻² for San Cristóbal. Other factors that affect solar irradiance directly are the relative humidity percentage (%H). In Guayaquil, the relative humidity percentage is 72.1%. In Manta a relative humidity percentage

of 77.3% is recorded and in San Cristóbal, a relative humidity percentage of 51.1% is recorded. The city of Guayaquil has the highest Total sky cover and the island of San Cristóbal has the lowest relative humidity.

As can be seen in Figure 10, in winter the solar irradiance and the ambient temperature is higher than in summer. In the winter the maximum solar irradiance is $1026.2 \text{ W}\cdot\text{m}^{-2}$ for Guayaquil, $1052.7 \text{ W}\cdot\text{m}^{-2}$ for Manta, and $1074.9 \text{ W}\cdot\text{m}^{-2}$ for San Cristóbal and the average ambient temperature is 26.8°C for Guayaquil, 26.4°C for Manta, and 25.8°C for San Cristóbal. While in the summer solar irradiance maxima are $1025 \text{ W}\cdot\text{m}^{-2}$ for Guayaquil, $1041.9 \text{ W}\cdot\text{m}^{-2}$ for Manta, and $1075.5 \text{ W}\cdot\text{m}^{-2}$ for San Cristóbal, and the average ambient temperature is 24.7°C for Guayaquil, 21.9°C for Manta, and 24.0°C for San Cristóbal.

Figure 11 shows that solar irradiance is more intense in Manta and San Cristóbal. The solar irradiance reaches a maximum value is $1024.4 \text{ W}\cdot\text{m}^{-2}$. The minimum value of solar irradiance occurs in Guayaquil registering a value of $833.3 \text{ W}\cdot\text{m}^{-2}$. This lower value in Guayaquil of solar irradiance can be attributed to pollution and humidity.

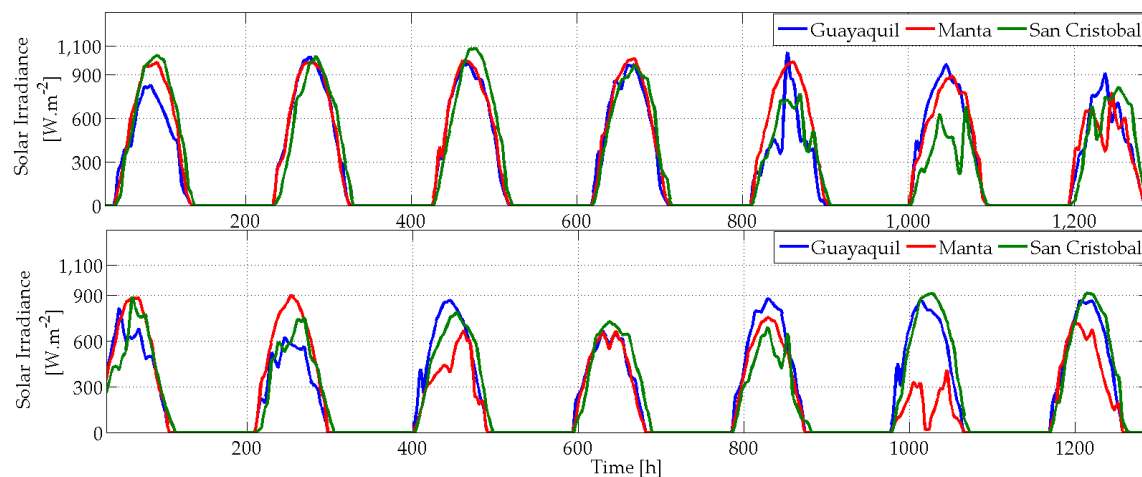


Figure 11. Solar irradiance in three selected sites of Ecuador from 8–14 February and 13–19 July.

February is the most solar irradiance provided in Figure 12, the thermal energy collected by the solar collector field in the three cities evaluated is shown. Manta and San Cristóbal have higher values compared to Guayaquil. The maximum rate of thermal energy obtained in Manta and San Cristóbal is 1.98 MW and 1.86 MW, respectively. While the maximum rate in Guayaquil is 1.82 MW.

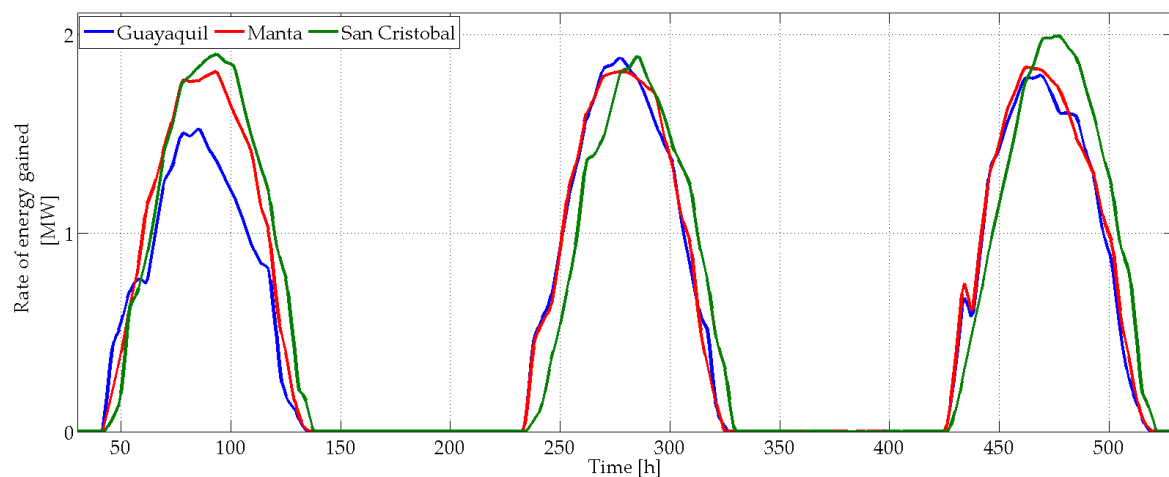


Figure 12. The collector thermal power gained for the selected sites of Ecuador.

The temperature at the exit of the site of the HTF registered in the 7 days of the month of February. As it is possible to see in Figure 13 the highest temperature values registered in the three cities are 361 °C in San Cristóbal, 341 °C in Manta, and 327 °C in Guayaquil. The above results can be attributed to the high irradiance value of the solar irradiance and to the ambient temperature in the areas closest to the sea in Ecuador.

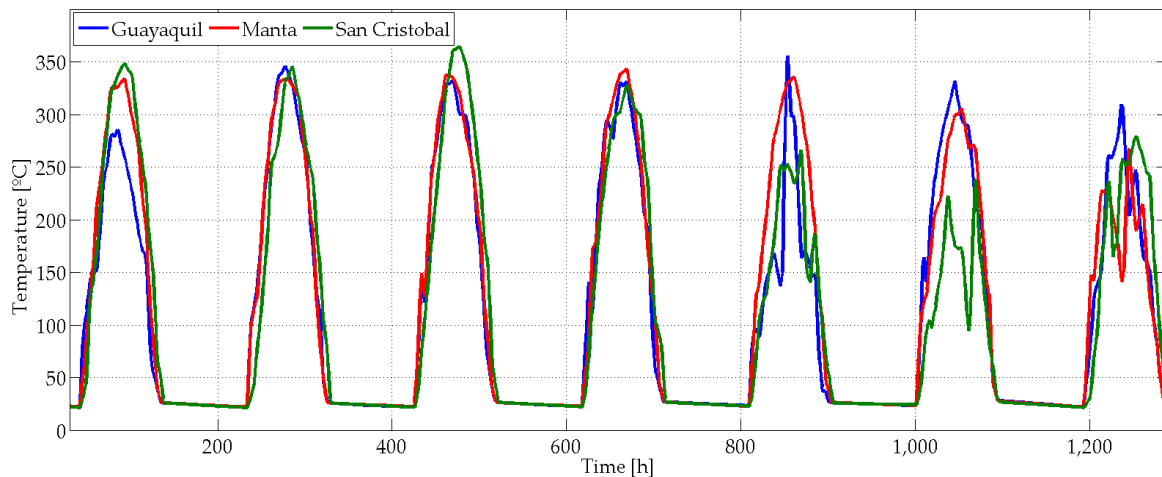


Figure 13. The Heat Transfer Fluid (HTF) Outlet temperature from the solar collector field seven days for the selected sites of Ecuador.

Figure 14 illustrates the annual thermal energy obtained from SCF and the annual electric power generated for the selected cities. We can observe that the highest annual energy obtained by the solar concentrator is reached in San Cristóbal, where it registers 3664.3 MW, while the electrical energy generated is of 1090.7 MW. The lowest annual energy obtained by the solar concentrator is obtained in Guayaquil, where it registers a value of 3314.8 MW, while the electric power generated is 986.4 MW.

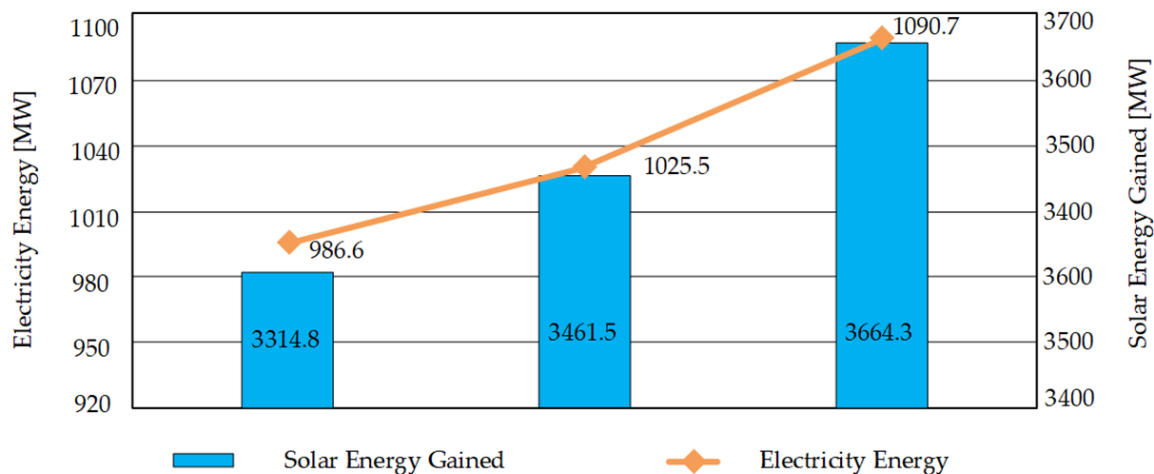


Figure 14. The annual collector energy gained and electric energy for selected sites.

Figure 15 presents the instantaneous efficiency of the plant, which is defined as the electric power rate obtained from the total divided electric generator incident beam radiation falling concentrator area for the three selected cities. From the comparison, we observed that the variation of efficiency in the three cities is similar, covering a minimum efficiency of 31.1% and a maximum efficiency of 41.1% in the last hour of the afternoon for the three cities.

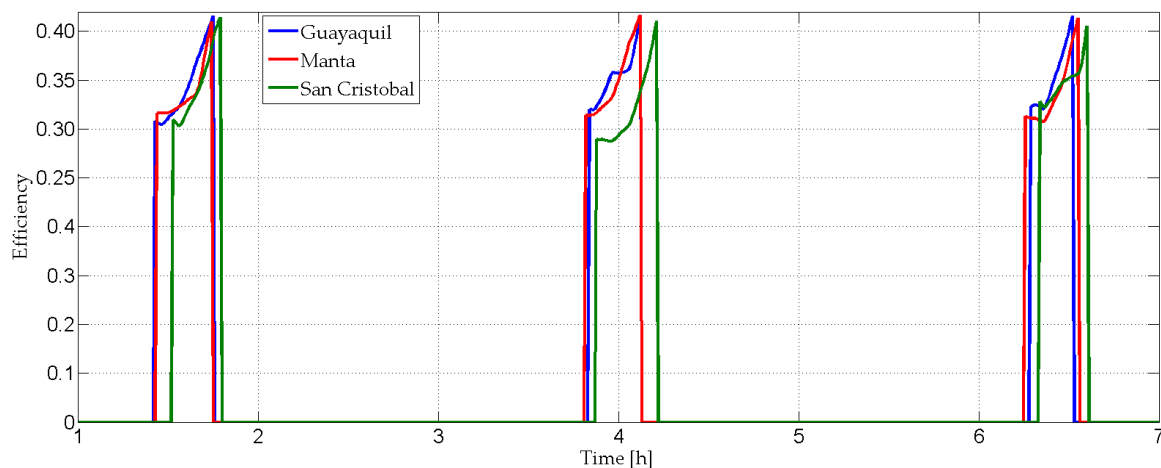


Figure 15. The overall efficiency of the solar power plant for the Guayaquil, Manta, and San Cristóbal during three days in February.

4. CO₂ Emissions

To find out how much CO₂ emissions are avoided using thermo-solar energy, information was collected from the Electricity Regulation and Control Agency (ARCONEL) [35]. In Figure 16, the trend line shows gross electricity production, which is the sum of the amount of electricity generated by the country's existing infrastructure and the energy imported from Colombia and Peru. Bars display the amount of tCO₂ generated annually [36]. In Table 4, fuel consumption for gross electricity production in the period 2011–2018 are shown. The CO₂ emission factor and the density of the different fuels used in the thermal generators are visible in the nomenclature table.

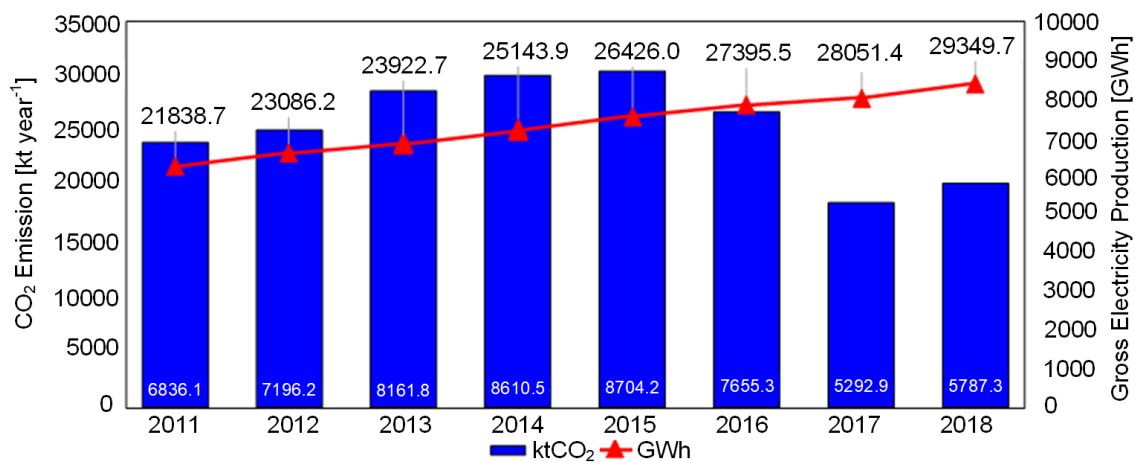


Figure 16. Evolution of CO₂ emission margins and Gross Electricity Production.

Table 4. Consumption of fuel used in electricity generation.

Fuel (Units Million)	2011	2012	2013	2014	2015	2016	2017	2018
Fuel oil (l)	1208.8	1421.6	1561.6	1676.6	1526.6	1136.1	645.1	843.3
Diesel (l)	783.3	60.0	804.2	843.8	965.6	842.4	491.9	519.6
Naphtha (l)	66.8	0.5	12.3	0.0	0.0	0.0	0.0	0.0
Natural gas (m ³)	518.8	680.0	759.1	782.6	753.9	767.9	688.8	592.1
Waste (l)	155.0	149.6	145.9	164.6	267.2	225.5	129.6	130.0
Crude (l)	285.5	3055.0	343.7	350.5	341.5	456.4	461.4	508.7
LPG (l)	32.3	28.6	26.8	28.6	33.2	37.7	32.3	35.9
Cane bagasse (t)	1064.3	1122.3	343.5	1447.7	1504.4	1542.8	1668.5	1437.1
Biogas (m3)	0	0	0	0	0	8,119,299.9	16,327,344.0	26,622,714.2

To calculate the emissions of primary air pollutants and CO₂, the basic model used in jobs such as [37,38] was applied, resulting in Equation (9).

$$EF_{EL,k,y} = \frac{\sum_i FC_{i,y} \cdot E_{Edw,i,y} \cdot EF_{CO_2,i,y}}{EG_{k,y}} \quad (9)$$

where:

- $EF_{EL,k,y}$, CO₂ emission factor of the generation units m in the year y (tCO₂·MWh⁻¹);
- $FC_{i,y}$, Quantity of fossil fuel type i consumed in the year y of the generation units m ;
- $E_{Edw,i,y}$, Energy density by weight of fossil fuel type i in the year y ;
- $EF_{CO_2,i,y}$, CO₂ emission factor by fuel type i in the year y (tCO₂·MWh⁻¹);
- $EG_{k,y}$, Net energy generated in the year and except for low-cost units (MWh);
- k , All grid-connected generation units in the year y except low-cost units;
- i , All fuels used by generation units in the year y ;
- y , Year corresponding to the data used for the analysis.

4.1. Emission Factor

The gross electricity generation is calculated with the data from Table 5 the CO₂ emissions produced. The CO₂ emission factor for each unit of electricity available for consumption is established by dividing the total net emissions from Table 6 by the gross electricity production plus imported energy values from Figure 15. The results are shown in Figure 16, which indicates that annual CO₂ emissions due to gross electricity generation in Ecuador in the period 2011–2018 ranged between emission 5787.3 and 8704.2 ktCO₂·year⁻¹.

Table 5. CO₂ emissions (kt·year⁻¹) due to gross electricity generation in Ecuador.

Fuel	2011	2012	2013	2014	2015	2016	2017	2018
Fuel oil	2970.9	3493.5	3838.0	4120.5	3751.4	2792.8	1583	2072.8
Diesel	1755.2	1417.8	1802.3	1890.7	2163.7	1887.7	1102.7	1164.5
Naphtha	134.6	0.8	24.7	0	0	0	0	0
Natural gas	907.7	1190.6	1327.5	1365.9	1318.3	1341.9	1206	1035.9
Waste	381.5	367.2	358.8	405.1	656.9	554.2	318.1	319.7
Crude	644.3	688.9	775.5	790.8	770.6	1029.6	1041.1	1147.6
Liquefied gas Petroleum	41.9	37.3	35.0	37.6	43.2	49.2	42.1	46.9
* Cane bagasse	827.4	872.5	850.0	1124.9	1169.6	1199.4	1297.1	1117.2
* Biogas	0	0	0	0	0	8897.1		29,173
Total	6836.1	7196.1	8161.8	8610.5	8704.2	7655.3	5292.9	5787.3

* Total net emissions do not include sugar cane and biogas values. Considering that, being biomass, its. Combustion does not generate net CO₂ emissions.

Table 6. Life Cycle (LC) Impact Metrics by System and Phase for CSP Designs.

Life Cycle Phase	Plant System	GHG (g CO ₂ eq·kWh ⁻¹)
Manufacturing		13
Construction	HTF	1.8
Operation	Power plant	11
Dismantling	Solar field	0.12
Disposal	TES	2.1
Grand total		26

The International Energy Agency [39] reports the average value of the emission factor for Ecuador, for the period 2011–2018, equal to 337.5 gCO₂·kWh⁻¹. The average value for the period 2011–2018 in Figure 17 is equal to 331.2 gCO₂·kWh⁻¹. These mean values are congruent with a difference of 3.75%.

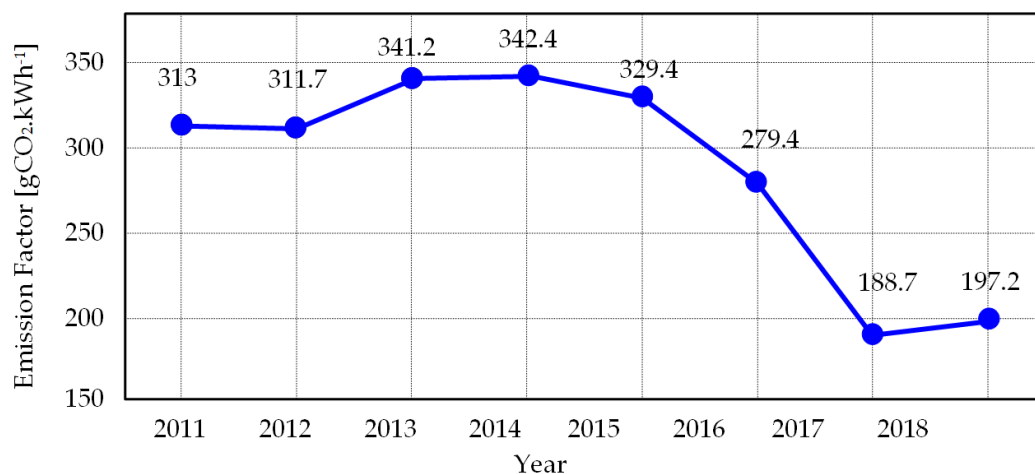


Figure 17. CO₂ emission factor (g·kWh⁻¹) for electricity generation in Ecuador.

The CO₂ emission factor for each unit of electricity available for consumption ranged from 188.7 to 342.4 gCO₂·kWh⁻¹. The highest value of the emission factor corresponds to the year 2014, as can be seen in Figure 18, the year with the highest percentage of participation of non-renewable sources (49.1%). The lowest value (188.7 gCO₂·kWh⁻¹) corresponds to 2017, the year with the lowest share of non-renewable sources (73.6%).

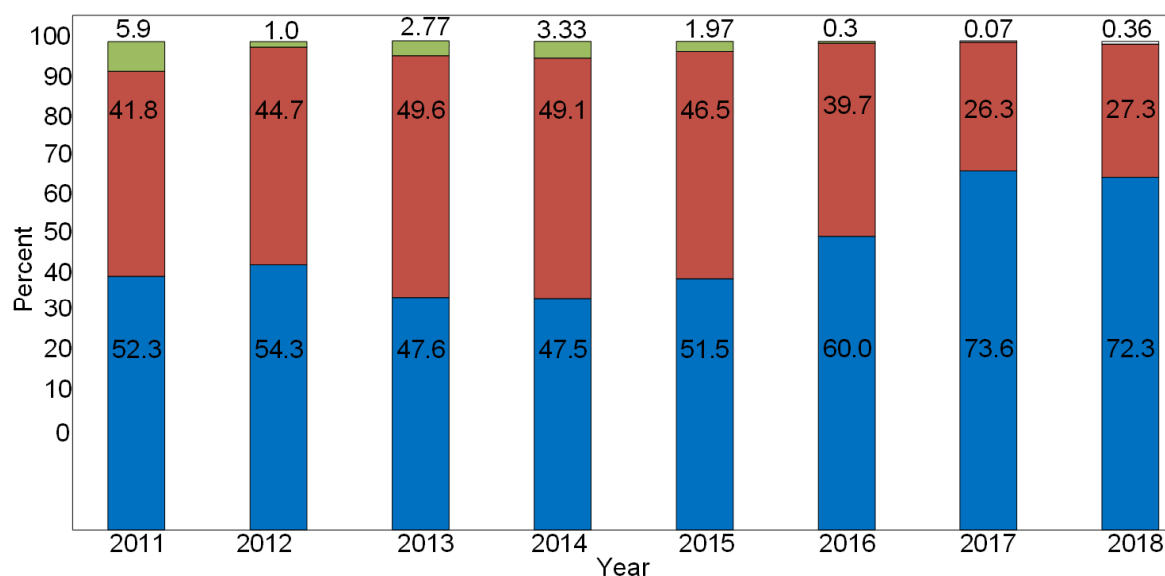


Figure 18. Percentage composition of electricity generation in Ecuador.

The CO₂ emission factor for the unit consumption of electricity is used at various levels: national, regional, local, institutional, family, and personal; in evaluations of sustainability indicators, such as the carbon footprint and the ecological footprint. It is a basic parameter in energy planning to evaluate the change of emissions with new configurations of the energy matrix or mix.

Burkhardt et al. [40,41] performed the Life Cycle Assessment (LCA) of a Parabolic Trough Concentrating Solar Power (CSP) plant to define the impacts of the main design alternatives for this type of plant.

LCA is recognized as a holistic and standard approach for quantifying the environmental impacts of renewable energy (RE) technologies. LCA accounts for the impacts resulting from upstream and downstream activities over the life cycle (LC) of a power plant. The authors used a hybrid analysis,

where, the system is modeled of component masses and process energy flows, and the categories of costs are translated to environmental impacts via economic input-output.

According to the guidelines described in the international standard series ISO 14040-44 [42], the hybrid LCA evaluates the following LC phases of the proposed trough plant: Manufacturing, construction, operation, and maintenance (O&M, dismantling, and disposal).

Life cycles of the following systems are evaluated to identify areas of high impact: HTF system, solar field system, TES system, and power plant system.

Through the software SimaPro LCA modeling software and the EcoInvent life cycle inventory (LCI) database, Burkhardt et al. provide greenhouse gas (GHG) emissions of select components and systems. Where GHGs are Emissions of individual GHGs from the CSP plant LC are presented as the sum of each GHG weighted by its 100-year global warming potential (GWP)³ to obtain grams of CO₂ equivalents (g CO₂eq·kWh^{−1}). In addition, they are presented as a summary in Table 6.

4.2. Results and Discussion of Emission Factors

Table 7 shows the CO₂ emissions by the energy generation of the solar thermal power generation plant. Using a conversion factor of 0.8 kgCO₂·kWh^{−1}, the CO₂ emissions were calculated. The conversion factor was calculated in the Wind Project Isla San Cristóbal [43]. In its study on the CO₂ emission factor due to electricity generation in the Galapagos Islands. The CO₂ emission factor for mainland Ecuador was 0.197 kgCO₂·kWh^{−1}. The CO₂ emission factor for Galapagos is four times higher than that of Ecuador because on the continent energy is obtained from various sources, such as burning fossil fuels and hydroelectric, while in Galapagos, non-renewable energy is produced solely by burning fossil fuels. On the other hand, to calculate the emissions produced by the CSPs due to their maintenance and other variables that were explained above, an emission factor of 0.026 g CO₂·h^{−1} will be used. Although this emission factor was calculated for a CSP of greater dimensions than those presented in this work, it serves as a reference value for the calculation.

Table 7. CO₂ emissions avoided by the generation of thermo-solar plants.

Selected Sites	Electricity Energy MWh	Gallons Saved	Invoicing Dollars	Emissions TON CO ₂ Generated by the Thermo-Solar Plant	Emissions TON CO ₂ Avoided When Not Using Fuel	Total Emissions TON CO ₂ Avoided
Guayaquil	411.1	35,747.8	52,703.0	10.7	81.0	70.3
Manta	497.2	43,234.8	63,741.0	12.9	98.0	85.1
San Cristóbal	680.6	59,182.6	87,252.9	17.7	544.4	526.7

5. Conclusions

In conclusion, the cities being close to latitude 0 have a large amount of solar irradiance throughout the year. Achieving high temperatures in the HTF in winter and summer is ideal for the operation of solar plants. The total annual solar thermal energy obtained from the selected sites is 3664.3 MW in San Cristóbal, 3461.5 MW in Manta, and 3314.8 MW in Guayaquil. Manta and Guayaquil are large cities located on the continent. Hydroelectric plants supply their electricity consumption. The city of San Cristóbal is an island located in the Galápagos archipelago.

The electricity consumption of San Cristóbal is largely covered by thermal generation (fossil fuels) and, to a lesser extent, by wind and photovoltaic generation. The implementation of thermos-solar plants in the islands allows for the reduction in the consumption of fossil fuels and CO₂ emissions. Investing in solar thermal generation systems is more recommendable on the island of San Cristóbal.

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Nomenclature

Symbol	Description Unit
A_{cs}	Collector absorber cross-sectional area (m^2)
C_p	Specific heat capacity ($J \cdot ^\circ C^{-1} \cdot kg^{-1}$)
C_f	Conversion factor to account for the number of modules, connections, and $kg \cdot h^{-1}$ conversion ($n_p \cdot n_t \cdot kg \cdot h^{-1} \cdot m^{-3}$)
$d_{tout-tin}$	Outlet fluid temperature-inlet fluid temperature-related transport delay in
$f(x_k)$	Output signal function
$FC_{i,y}$	Quantity of fossil fuel type i consumed in the year y of the generation units m (kg)
$E_{Edw-i,y}$	Energy density by weight of fossil fuel type i in the year y ($MWh \cdot kg^{-1}$)
$EF_{EL-k,y}$	CO ₂ emission factor of the generation units m in the year y ($tCO_2 \cdot MWh^{-1}$)
$EF_{CO_2-i,y}$	CO ₂ emission factor by fuel type i in the year y ($tCO_2 \cdot MWh^{-1}$)
$EG_{k,y}$	Net energy generated in the year and except for low-cost units (MWh)
G	Collector aperture (m)
H_l	Thermal losses coefficient ($W \cdot ^\circ C^{-1}$)
H_1	Linear function of thermal losses (W)
i	Fuels used by generation units m in the
I	Year solar irradiance ($W \cdot m^{-2}$)
k	Generation units connected to the grid in the year y
K_{opt}	Optical efficiency
L	Loop pipe length (m)
L_{eq}	Equivalent length of the collector (m)
$\dot{m}$	Primary circuit mass flow rate ($kg \cdot s^{-1}$)
n_o	Geometric efficiency (Unitless)
n_l	Number of operational loops (Unitless)
n_p	Number of parallel collectors in each loop-row (Unitless)
n_t	Number of serial tubes in each collector (Unitless)
Q_{loop}	Volumetric flow rate in the loop ($kg \cdot h^{-1}$)
Q_{PCS}	Volumetric flow rate in Power Conversion System ($kg \cdot h^{-1}$)
Q_{SCF}	Volumetric flow rate in solar field collector ($kg \cdot h^{-1}$)
T_a	Ambient temperature ($^\circ C$)
T_m	Mean fluid temperature ($^\circ C$)
$T_{loop,in}$	Inlet temperature of the loop ($^\circ C$)
$T_{loop,out}$	Outlet temperature of the loop ($^\circ C$)
$T_{PCS,in}$	Inlet temperature in the Power Conversion System ($^\circ C$)
$T_{PCS,out}$	Outlet temperature in the Power Conversion System ($^\circ C$)
$T_{SCF,in}$	Inlet temperature of the solar field collector ($^\circ C$)
$T_{SCF,out}$	Outlet temperature of the solar field collector ($^\circ C$)
v	Flow rate ($m \cdot s^{-1}$)
x_k	Tracking error
y	Controlled variable
y_{set}	Set-point

Greek symbol

Δh	Increased enthalpy ($\text{J}\cdot\text{kg}^{-1}$)
ρ	Water density ($\text{kg}\cdot\text{m}^{-3}$)
LPG	Liquefied Petroleum Gas (l)

Density

Value		Unit	
944.0	$\text{kg}\cdot\text{m}^{-3}$	11.2	$\text{kWh}\cdot\text{kg}^{-1}$
850.0	$\text{kg}\cdot\text{m}^{-3}$	11.6	$\text{kWh}\cdot\text{kg}^{-1}$
739.0	$\text{kg}\cdot\text{m}^{-3}$	12.4	$\text{kWh}\cdot\text{kg}^{-1}$
0.67	$\text{kg}\cdot\text{m}^{-3}$	10.7	$\text{kWh}\cdot\text{kg}^{-1}$
944.0	$\text{kg}\cdot\text{m}^{-3}$	2.2	$\text{kWh}\cdot\text{kg}^{-1}$
874.0	$\text{kg}\cdot\text{m}^{-3}$	11.6	$\text{kWh}\cdot\text{kg}^{-1}$
528.6	$\text{kg}\cdot\text{m}^{-3}$	13.7	$\text{kWh}\cdot\text{kg}^{-1}$
120.0	$\text{kg}\cdot\text{m}^{-3}$	4.76	$\text{kWh}\cdot\text{kg}^{-1}$
1.15	$\text{kg}\cdot\text{m}^{-3}$	1.48	$\text{kWh}\cdot\text{kg}^{-1}$

Energy Density by Weight**References**

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