energies

MDPI

Article

A Feasibility Analysis of a Solar Power Plant with Direct Steam Generation System in Sonora, Mexico

Ernesto Enciso Contreras [1], Juan Gabriel Barbosa Saldaña [2,*], Jesus de la Cruz Alejo [1], Claudia Del C. Gutiérrez Torres [2], Jose Alfredo Jimenez Bernal [2] and Maria Belem Arce Vazquez [1]

[1] Tecnológico Nacional de México, Tecnológico de Estudios Superiores de Ecatepec, Ecatepec de Morelos 55210, Mexico
[2] Instituto Politécnico Nacional, SEPI-Mecanica-ESIME-Zacatenco, Ciudad de Mexico 07738, Mexico
* Correspondence: jbarbosas@ipn.mx

Abstract: Power generation using renewable technologies has become a primordial option to satisfy the energy demand all over the world, with solar concentrating technologies widely applied for this purpose. A combination of a parabolic trough collector with direct steam generation has been considered an excellent option for power generation as the economic cost and complexity in the plant are reduced. The thermal evaluation of a solar power plant as well as the PTC in the DSG process is very important in viability and economic analyses. In this sense, as the main objective of this work, a numerical tool for evaluating DSG with PTC technology was developed. The SOLEEC software is a versatile, reliable, accurate, and user-friendly option to thermally evaluate a DSG with PTC technology. The user has the possibility of comparing the thermal behavior of different geometrical dimensions for a PTC and even consider different materials to satisfy the demand of superheated steam by a DSG process. The software has an error of less than 5% when compared with the literature results and was used in this paper to evaluate a power plant in Mexico, showing that the change to DSG proposing different PTC could reduce the solar field by about 35%.

Keywords: PTC; DSG; solar energy; power plant

Citation: Enciso Contreras, E.; Saldaña, J.G.B.; Alejo, J.d.l.C.; Torres, C.D.C.G.; Bernal, J.A.J.; Vazquez, M.B.A. A Feasibility Analysis of a Solar Power Plant with Direct Steam Generation System in Sonora, Mexico. *Energies* **2023**, *16*, 4388. https://doi.org/10.3390/en16114388

Academic Editors: Kegong Fang, Gangli Zhu, Ying Yang and Shenghua Liu

Received: 2 March 2023
Revised: 12 May 2023
Accepted: 19 May 2023
Published: 29 May 2023

1. Introduction

Currently, the demand for energy worldwide is constantly increasing and technologies based on fossil fuels are used to meet the requirements of modern society. In this sense, the excessive use of fossil fuels has produced consequences and irreversible damage to the environment. The waste pollution gases by combustion are the main factor that contribute to global warming, causing an increase in global temperature, and consequently, an irreversible deterioration of the environment and its ecosystems.

The use of renewable technologies to produce energy is an alternative to reduce this destructive trend. In this sense, solar energy has the potential to meet the needs of global energy demand because is an inexhaustible, abundant, reliable, and clean resource. Mitigating the global warming by the substitution of fossil fuel power by solar power will be, in a short time, environmentally, economically, and socially beneficial to the entire world. A constant effort to implement solar energy technologies will result in a beneficial reduction in CO_2 emissions by 2050, while on the other hand, the non-implementation of sustainable energies will jeopardize the future of the planet [1–4].

In this sense, a point that has recently become of interest in the scientific community is the combination of traditional power plants and the application of solar technology. The result has been the hybridization of power plants that use a traditional combined cycle with solar technology (ISCC). Mainly, the solar technology is the PTC, one of the most mature devices to convert the incident solar irradiation into sensible heat by heating a working fluid with a high operating temperature range, normally up to 300 °C [4,5].

PTC technology is highly efficient, even at elevated levels of temperature, and are widely used in ISCC power plants; moreover, PTC technology is capable of directly generating steam (DSG), resulting in an increment in the affordability of the power plant. The sizing and optimization of an ISCC-PTC-DSG is extremely important because of the cost investment. Therefore, it is important to have reliable tools and procedures to thermally evaluate and predict the behavior and performance of such power plants [6].

For example, a study that looked at predicting the performance of an ISSC-PTC installed in Aswan City, Egypt demonstrated that the plant capacity increased by 50 MW in the summer months, having an annual reduction in gas emissions close to 51,670.8 tons [4]. The authors used Mathcad models, Excel, and Water Steam Pro to analyze the thermodynamic performance of the plant.

The Kurymat power plant, installed at South Cairo, Egypt, uses the PTC technology to generate the steam during the daytime. The plant was modeled and numerically simulated using the TRNSYS software and the results were compared with the measured data of the power plant and the numerical results were in close agreement with the measurements [7].

The application of PTC combined with a steam Rankine, an organic Rankine cycle with the capacity to store heat for operating when solar irradiance is not present, was analyzed by means of multi-objective optimization using the PSO algorithm with the addition of EES and MATLAB. The PSO algorithm selects the best designing variables, and the results showed that 59% of the total exergy destruction happens on the solar collector [8].

A model based on an energy balance in PTC collectors was used to determine the main operative parameters of a typical power plant. The simulation considered forced convection inside the solar absorber tube and the model was verified using heat data from a solar thermal power plant located in Spain. The heat generated in similar conditions of a solar collector in the region with a temperate climate in the city of Bialystok, Poland was determined by the model for different months of the year. The results showed that the energy obtained from the same area of concentrated solar collectors was eight times lower compared to the installation in Spain [9].

Another work investigated the performance of a conventional steam power plant retrofitted with a solar-assisted regenerative system using parabolic trough solar collectors, where the steam power plant was located in Kuwait, which received high solar radiation levels. The results showed that removing the low-pressure turbine extractions enhanced the performance of the solar power plant by 9.8 MW with an aperture area of 25.850 m^2, a techno-economic analysis was also used to estimate the levelized cost of energy; this power plant, compared to a conventional photovoltaic solar plant, reduced the total aperture area to 45% and 44% [10].

Different numerical tools such as TRNSYS-STEC, GateCycle, Termoflex, SAM, models in MATLAB, CYCLO-Tempo, TRNSYS, mathematical models in FORTRAN, IPSEpro, models in Mathcad, PSO with EES and MATLAB, just to mention a few, have been used to predict the behavior and performance of ISCC-PTC-DSG power plants [5]. However, none of them were based on the theory of phase change in the PTC as the software presented here does.

In this paper, the thermal evaluation of a solar power plant by means of a numerical tool for evaluating DSG with PTC technology was developed. The software offers the user the possibility of comparing the thermal behavior of different geometrical dimensions for a PTC and even considers different materials to satisfy the demand of superheated steam by a DSG process. The objective was to use this novel numerical tool to analyze the feasibility of implementing ISCC-PTC-DSG in substituting the actual configuration of a CC power plant in Mexico that uses a PTC field with a synthetic oil as the heat transfer substance.

2. Materials and Methods

A PTC collector is a solar device used to convert the irradiation solar energy reached on the collector's aperture into heat energy absorbed by a heat transfer fluid (HTF), which flows inside the absorber tube, so the amount of heat available is increased due to the optical and geometrical configuration.

PTC and DSG Generation

The performance of a PTC depends on the construction material as well as the geometrical dimensions. A high reflectivity is required for the parabolic surface to reflect the incident radiant energy toward the absorber pipe, which should be an excellent heat conductor, and it is covered up with a paint coating to obtain a selective surface, reduce the energy loss, and improve the conversion process by supplying the maximum energy to the HTF or working substance. Sometimes, the absorber pipe is enveloped by a transparent cover to reduce the heat convection to the surroundings; in this sense, the transparent cover must have a high value of transmittance and low absorptance. Resistance to the thermal stresses is another quality for the construction material due to the high temperature gradients found in the PTC systems.

The PTC technology has an ample application range, from low temperature to high temperature ones. For low temperature applications, the HTF does not experiment on a phase change, and many devices use water as working fluid as the maximum temperature reached is below the saturation point. The applications are mainly used for heating water in hospitals, hotels, swimming pools, or small applications for industry uses. When higher temperatures are required, the application of thermal oils for HTF in the PTC is commonly used and the temperature reached is around the 400 °C [11]. However, the addition of a heat exchanger is required for steam generation. This last step increases the cost of the installations and generates a loss of energy in the heat transfer process. In several cases, the implementation of these devices for power generation increases the cost of the thermal plant and complicates its configuration, as a result, its implementation has become prohibitive.

Recently, many devices and technological configurations have been studied to obtain steam directly (DSG) from the absorber tube. Three different configurations have been studied. The first one is the once-through, where the water entering is turned into steam in the same pipeline of the absorber. The second one is recirculation mode; in this case, a drop separator is installed between the saturated steam section and the superheated steam: the separator returns the liquid water to the inlet of the collector. Finally, the third option is the injection mode, where the absorber tube is divided into many stretches and an injection valve is installed at the start of every section [12]. The most studied configuration is the once-through due to there being less complexity in the installation. The principal point of DSG generation is a cost reduction and to avoid the need of heat exchangers between the solar collector and the steam turbine. On the other hand, some problems are presented during the steam generation because the flow stratification in the absorber tube induces strong thermal stresses, and in some cases, deformation, leaks, and severe damage in the absorber tube of the PTC collector are presented.

The next section shows the mathematical models for the heat transfer along the absorber pipe that will be used in the software to compute the heat coefficients in the PTC collectors.

3. Mathematical Model

DSG generation based on parabolic trough solar collectors can be simplified for analysis by considering them as horizontal pipes with a constant heat flux at the outer boundary, while in the interior, a forced evaporation phenomenon is developing. The evaporative process can be divided into three different heating zones: saturated liquid where the temperature is less than the saturation liquid temperature when the fluid enters the absorber, then the steam generation zone where the fluid goes through several flow patrons until reaching the saturated steam condition. Finally, there is the reheating zone, where the steam reaches the desired steam condition. In the first and last heating zones, the HTF will be considered as a one phase fully developed fluid. The HTF goes into the collector as a subcooled fluid and when passing through the collector, the fluid temperature and wall temperature increase in the flow direction, and the mean temperature can be computed by means of an energy balance in the axial direction. Similarly, once the HTF has become steam, it will be treated as a one phase fluid. This zone is critical because as the heat flux remains constant at the boundary, and the sudden diminution in the heat transfer coefficient carries a sudden increase in the wall temperature, which can cause severe damage in the duct. Several studies have considered that this critical situation is because the liquid film in the annular regime has evaporated because of the heating flux conditions in the wall [13].

In zones 1 and 3, the heat transfer coefficient will be computed using the classical model for a fully developed flow in one phase for circular pipes. The heat transfer coefficient for fully developed flow in pipes depends on the flow regime and in the heat imposed on the pipe wall as the boundary. For the turbulent regime, the Nusselt is a function of the Reynolds, the Prandtl, and the friction factor. Gnielinski developed a correlation valid for several Reynolds including the transition zone with a maximum of 10% error when compared with the experimental data [14].

In the evaporative zone or changing phase zone, the liquid and steam are at saturation conditions and the heat at the wall produces the latent thermal energy for the evaporation process. Here, the assumptions of a horizontal smooth pipe will be applied. The flow patterns and the heat transfer are a function of the temperature differences between the wall and the fluid saturation temperature as well as the fluid properties.

The heat radiant energy supplied is captured by the receiver pipe, which induces changes in the flow going from a saturated liquid to a saturated steam. The flow goes through different patterns [15], as shown in Figure 1. As the mass flow is higher, the flow pattern is more symmetric and stable, which occurred in the vertical ducts. In this sense, a high mass flow would be recommended by the PTC operation.

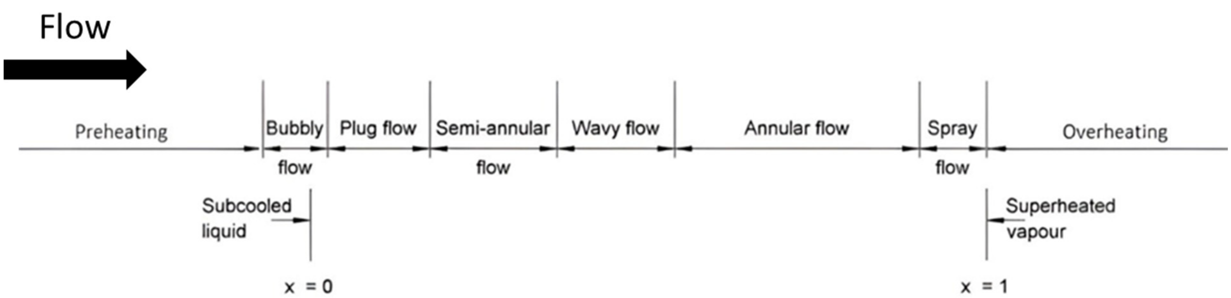

Figure 1. Flow patterns formed during the evaporation process considering the forced flow on horizontal tubes.

There are several correlations in the literature related to the evaporative forced convective heat transfer. Chen's correlation is the most widely used when water is considered; this correlation uses more than 600 experimental data for water in a vertical duct [16]. The approximation is good for water at low pressure but is not suitable for thermal oils or refrigerants. Gunger and Winterton combined the models of Chen and Shah, while Liu and Winterton showed a correlation based on more than ten thousand data for water, refrigerants, and cryogenic substances [13,17,18]. These data are suitable for a large variety of density relations for the liquid and vapor phases as well as different heat flux and mass flows. The effect of density and boiling number are critical for the computation. He presented a simple model for the convective effects and the nucleation by introducing an additional parameter for taking into account the effects of the fluid surface and the nucleate boiling dominant region and the convective boiling dominant region based on the convective number, boiling number and Froude number. The heat transfer is computed by the addition of the following equations:

$$h_{tp|NBD} = 0.6683Co^{-0.2}(1-x)^{0.8}f_2(Fr)h_l + 1058Bo^{0.7}(1-x)^{0.8}F_{Fl}h_l \quad (1)$$

$$h_{tp|CBD} = 1.136Co^{-0.9}(1-x)^{0.8} f_2(Fr)h_l + 667.2Bo^{0.7}(1-x)^{0.8} F_{Fl}h_l \quad (2)$$

where *NBD* and *CBD* refer to the nucleate boiling dominant and convective boiling dominant, respectively. The dimensionless parameters are the convective number (*Co*), the boiling number (*Bo*), and the Froude number (*Fr*), according to Equations (3)–(5), respectively:

$$Co = \left(\frac{\rho_g}{\rho_l}\right)^{0.5} \left(\frac{1-x}{x}\right)^{0.8} \quad (3)$$

$$Bo = \frac{\dot{q}}{\dot{m}h_{lg}} \quad (4)$$

$$Fr = \frac{\dot{m}^2}{\rho_l^2 g d_i} \quad (5)$$

The Froude multiplier $f_2(Fr)$ for horizontal smooth pipes is defined as:

$$f_2(Fr) = \begin{cases} Fr < 0.04 & (25Fr)^{0.3} \\ Fr \geq 0.04 & 1 \end{cases} \quad (6)$$

The heat transfer coefficient for the liquid phase (h_l) is computed according the Gnielinski correlation for $0.5 \leq Pr_l \leq 2300$ and $2300 \leq Re_l < 10^4$.

$$h_l = \frac{(Re_l - 1000)Pr_l(f/2)(\lambda_l/d_i)}{1 + 12.7\left(Pr_l^{2/3} - 1\right)(f/2)^{0.5}} \quad (7)$$

However, for $0.5 \leq Pr_l \leq 2000$ and $10^4 \leq Re_l < 5 \times 10^6$, the Petukhov and Popov is used:

$$h_l = \frac{Re_l Pr_l(f/2)(\lambda_l/d)}{1.07 + 12.7\left(Pr_l^{2/3} - 1\right)(f/2)^{0.5}} \quad (8)$$

The friction factor is computed by Equation (9):

$$f = [1.58ln(Re_l) - 3.28]^{-2} \quad (9)$$

F_{Fl}, according to Kandlikar, is equal to unity for water [13].

The above mathematical procedure is the basis of computing the SOLEEC II software. A difference in the other numerical tools used to evaluate the ISSC-PTC-DSG plants compared to the software here presented is that it uses the equations of phase change and a two phase-flow model to design the evaporative zone in the PTC absorber.

4. Numerical Methodology

The software SOLEEC was coded to run in the MATLAB platform. The reason for this choice was because of the large quantity of operations and the versatility of MATLAB in processing vectorial arrays as well as the easiness to develop graphic interfaces.

For a DSG with a PTC design, the absorber pipe is horizontal and the energy is uniform along the pipe. The water at the inlet, with a temperature lower than the saturation temperature for a given pressure, will increase until it reaches the saturation point, which then starts the phase change; first, the nucleation and then after, the steam quality increases, several different flow patterns occur as the evaporative convection is presented. The heat transfer coefficient in the phase change is influenced by the bubble generation and the liquid film on the wall. The saturated water is completely converted into steam and the heat coefficient is reduced. The maximum in the heat transfer coefficient is found in the change in phase when the steam quality reaches the value of x = 0.8 [19].

The numerical methodology considered in SOLEEC to compute the conditions from saturated water to super heating steam at the pressure given was divided into three parts for simplification. First, preheating until reaching the saturation point; second, is the evaporative section where the change from liquid to steam is given; and finally, the superheating zone, as is presented in Figure 2. Each zone is treated with a different mathematical model because, in fact, the HTF is changing and has different properties, thus, the mathematical model must be appropriate to calculate the heat transfer and pressure drop.

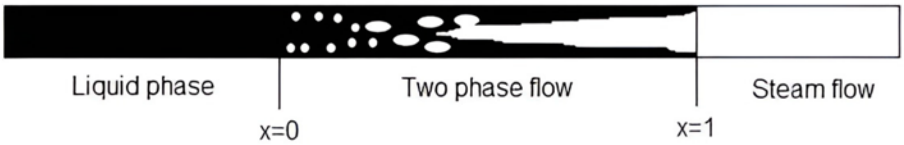

Figure 2. Sections in the absorber pipe in the DSG: preheating zone (liquid phase), evaporative zone (two-phase flow), and superheating zone (steam). The flow is from left to right. The letter x represents the steam quality.

The preheating is the first part of the absorber pipe. At the inlet, the water is at a temperature close to ambient, and at the exit, the saturation point for the given pressure should be reached. With the mass flux (kg/s) and the heat supply, the length of the pipe for this zone can be computed. The software makes the required interpolations to compute the thermal properties by considering the flow as a one phase flow or liquid phase [20]. Once the saturated temperature is reached, it starts evaporation or forced evaporation. The substance starts as a liquid, and at the exit, we find saturated steam. In this zone, the pressure and temperature are constants for the mass flow previously computed. Here, the heat transfer coefficient and the pressure drop are the most important parameters to define, and the models for nucleating and the flow patterns are used for the correct computation.

In the last section, the superheating process is considered. At the inlet, the flow is a saturated steam, and at the end of the absorber pipe, a superheating steam at the temperature and pressure desired. The flow mass remains constant from the other sections and is considered as a fully developed flow, and the mathematical models are those of one phase flow, while the software carries out double interpolated values for the properties of every point.

SOLEEC software is a computational tool for designing and evaluating DSG systems. The software allows for the evaluation of the solar resource for any location, and then by means of a succession of different windows, the software allows for the computation and evaluation of different geometrical dimensions for a DSG. In this sense, the software provides complete information on the thermal behavior of different PTC, which, according to the energy requirements, can supply the thermal demand considering the meteorological data and the solar energy supply. In a first stage, the software was planned for no phase change systems, but in an upgrade, the computing subroutines were introduced to consider the two-phase flow and the steam generation, so the result is a robust, versatile, and complete numerical tool for the analysis of these systems.

The principal advantage of the SOLEEC software is its ability to consider the geometrical dimensions as well as different materials of different PTCs (Table 1). The user can execute the program and make a comparison by choosing the best combination of parameters to supply the energy demand required. This numerical tool has become an auxiliary option for analyzing and designing thermal devices or thermal equipment because several combinations of different variables can be analyzed at low cost, and at the end, it is possible to choose the combinations of parameters that give the maximum efficiency and the best thermal behavior.

Table 1. Materials considered in the SOLEEC software.

PTC Component	Material
Reflective surface	Aluminum anodized Silver covering Acrylic aluminized
Selective surface	Black chrome Lead sulfate paint Copper oxide
Absorber pipe	Copper 3/4, 1, 2, 3, 4 (in) nominal diameter
Coating tube	Acrylic Borosilicate

The reliability, accuracy, and precision of every numerical tool must be proven by means of experimental data or the published results of other authors. In this sense, the SOLEEC software has been validated by several papers and textbooks. The validation process and detailed description of the software can be consulted in previously published work by the authors [20–22].

5. Results

The combined cycle power plant, 171 CC Agua Prieta II, is conditioned with a PTC, which produces the steam mass flow at the temperature and pressure conditions, generating 14 MW. Agua Prieta, Sonora, is located in the north of Mexico, latitude of 31.31° N, longitude of 109.53° W, and has a predominant desert climate, meaning that it is an excellent place for installing solar thermal systems due to the huge quantity of available solar radiation.

The inclusion of this solar field for steam generation using renewable energies diminishes the fossil fuel (natural gas) consumption, positively impacting the decrease in greenhouse gases, thus avoiding the emission of 17,760 tons of carbon dioxide (CO_2) per year. The solar field installed in the power plant uses 277 tons of synthetic oil as heat transfer fluid (HTF), reaching temperatures close to 500 °C. The HTF is pumped across the heat exchangers located in the Combined cycle power plant (CCPT) to produce saturated steam. The operative conditions of the solar field in the CCPT are summarized in Table 2.

Table 2. Operation conditions for the Agua Prieta Sonora II power plant.

Operative Conditions	Values
Guaranteed steam flow	74,140 kg/h (20.594 (kg/s))
Working pressure	130 bar
Steam temperature	330 °C

The solar–gas hybrid power plant at Agua Prieta II Sonora, consists of 34,944 mirrors and 3744 absorber tubes distributed in 26 rows. Each row is composed of four PTCs and each PTC has a length of 150 m. The solar field aperture is 300,000 m^2 and the total area of the solar field is about 600,000 m^2. The PTC rows are north–south oriented and the one-axis electromechanical positioning system allows the east–west rotation to diminish the solar irradiance incident angle and make better use of the solar resource. A schematic diagram of the integrated solar combined cycle power plant, Agua Prieta II, is shown in Figure 3.

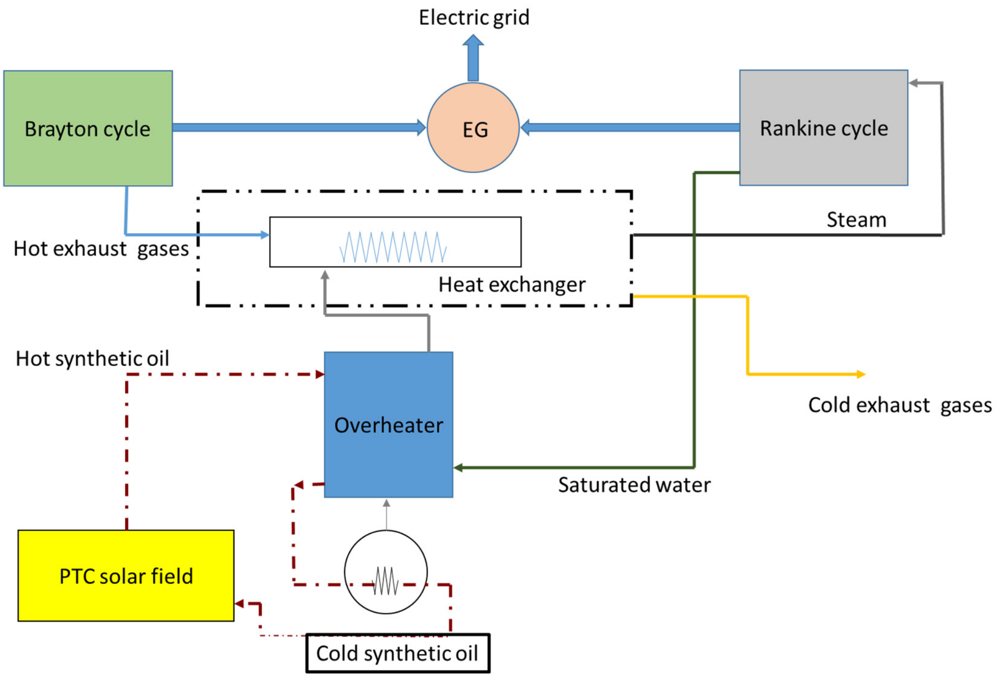

Figure 3. Schematic diagram of the integrated solar combined power plant, Agua Prieta II [23].

It should be understood that the operative conditions for the solar field of the CCPT requires a saturated steam at 330 °C at 130 bar, which means that the heat required to superheat the steam is provided by the exhausted hot gas from the gas turbine. The purpose of this work was to assess the feasibility of using a PTC collector with DSG in once-through mode in the mentioned power plant instead of a PTC solar collector field with synthetic oil. The SOLEEC software was used to determine the best configuration, the dimensions, flow, and thermal analysis of three different sizes of PTC collectors, which provide the steam demand by considering the operative parameters.

To execute the thermal evaluation, the SOLEEC software needs input data as the solar radiation in the place as well as some information on the construction materials for the PTC. In this case, the data from Table 3 were used for solar radiation and as for the materials, it was proposed that the absorber pipe for the PTC was made of copper because of its high conductivity and because this material presents a minimal deflection for high temperatures. In addition, for the reflective surface in the parabola, we chose anodized aluminum, black chrome as selective surface for the coper absorber, and borosilicate as the coating tube to cover up the absorber and reduce the heat loss.

Table 3. Agua Prieta's solar resource (https://power.larc.nasa.gov/data-access-viewer/ accessed on 12 December 2022).

Month	Solar Irradiation (kWh/m^2day)	Solar Insolation Hours for Representative Day	Solar Irradiance (W/m^2)
January	6.87	10.2	673.53
February	7.59	10.9	696.33
March	8.48	11.8	718.64
April	8.62	12.76	675.55
May	10.04	13.6	738.24
June	8.27	13.9	594.96
July	5.40	13.8	391.30
August	6.25	13.1	477.10
September	6.05	12.2	495.90
October	8.44	11.2	753.57
November	6.74	10.4	648.08
December	5.41	10	541.00
Annual average	7.34	11.98	617.01

Other geometric parameters such as parabola aperture, focal length, internal coating tube diameter, and coating tube thickness for the PTC are a function of the absorber diameter and it is the internal computing process of the software that estimates these dimensions according to the input data and the steam pressure, temperature, and mass flow required. For the purpose of analysis, three different diameters were proposed, and the geometric parameters of the PTC obtained from the software execution are presented in Table 4 for an absorber pipe with diameters of 1.0, 2.0, and 3.0 inches. Table 4 indicates that if the diameter in the absorber pipe augments the aperture, then the focal length also increases, which means that a larger parabola is needed for bigger absorber pipes.

Table 4. Geometric parabolic trough collector parameter for every diameter studied.

Diameter (in)	Aperture (m)	Focal Length (m)	Internal Coating Tube Diameter (m)	Coating Tube Thickness (m)
1	3.0545	0.7636	0.0666	0.0042
2	5.7695	1.4424	0.095	0.005
3	8.4846	2.1211	0.12	0.005

The combination of materials proposed in the software computing, considering a one-axis tracking system and a maximum solar irradiance angle, resulted in 69.42% for the optical efficiency for the PTC, which means that for the total solar irradiation reaching the parabola aperture, only 69.42% reached the absorber pipe and the other 30.58% was lost to the surroundings. The optical efficiency in the PTC was considered a good one, and indicates that the PTC has been suitably designed and is working properly.

By means of an iterative process based on the mathematical model presented, the SOLEEC software determines the flow, optimal length, and the energy balance for a PTC for DSG in once-through mode. The results of computing for 1.0 in, 2.0 in, and 3.0 inches for the absorber pipe diameter are presented in Table 5, Table 6, and Table 7, respectively. Note that the superheating length is not presented because the DSG was only for saturated steam according to the plant diagram.

Table 5. Analysis for the 1 inch absorber tube PTC collector.

Month	Preheating Section Length (m)	Evaporation Section Length (m)	Total Length (m)	Steam Mass Flow (kg/s)	Total Heat Gained (W)
January	8.036	6.675	14.711	0.0083	20,200
February	7.960	6.612	14.572	0.0085	20,700
March	7.985	6.633	14.618	0.0088	21,500
April	8.012	6.655	14.667	0.0083	20,200
May	8.038	6.677	14.715	0.0091	22,200
June	8.001	6.646	14.647	0.0073	17,800
July	7.999	6.645	14.644	0.0048	11,600
August	7.927	6.585	14.512	0.0058	14,100
September	8.021	6.663	14.684	0.0061	14,800
October	8.048	6.685	14.733	0.0093	22,700
November	7.949	6.603	14.552	0.0079	19,200
December	7.955	6.608	14.563	0.0066	16,100

Table 6. Analysis for the 2 inch absorber tube PTC collector.

Month	Preheating Section Length (m)	Evaporation Section Length (m)	Total Length (m)	Steam Mass Flow (kg/s)	Total Heat Gained (W)
January	14.864	12.347	27.211	0.0290	71,000
February	14.923	12.396	27.319	0.0301	73,700
March	14.892	12.370	27.262	0.0310	75,900
April	14.871	12.353	27.224	0.0291	71,300
May	14.918	12.392	27.310	0.0319	78,100
June	14.855	12.339	27.194	0.0256	62,700
July	14.645	12.165	26.810	0.0166	40,600
August	14.761	12.262	27.023	0.0204	49,900
September	14.759	12.260	27.019	0.0212	51,900
October	14.935	12.406	27.341	0.0326	79,800
November	14.862	12.345	27.207	0.0279	68,300
December	14.805	12.298	27.103	0.0232	56,800

Table 7. Analysis for the 3 inch absorber tube PTC collector.

Month	Preheating Section Length (m)	Evaporation Section Length (m)	Total Length (m)	Steam Mass Flow (kg/s)	Total Heat Gained (W)
January	21.819	18.124	39.943	0.0626	81,800
February	21.812	18.119	39.931	0.0647	84,600
March	21.854	18.153	40.007	0.0669	87,400
April	21.788	18.099	39.887	0.0627	82,000
May	21.846	18.147	39.993	0.0687	89,800
June	21.741	18.059	39.800	0.0551	72,000
July	21.358	17.741	39.099	0.0356	46,500
August	21.552	17.902	39.454	0.0438	57,200
September	21.587	17.931	39.518	0.0456	59,600
October	21.869	18.166	40.035	0.0702	91,800
November	21.770	18.084	39.854	0.0601	78,500
December	21.653	17.986	39.639	0.0499	65,200

Table 5 shows the PTC geometrical designing parameters for the 1″-diameter absorber for each month of the year. The total length was very similar for all months, with an average of 14.63 m. However, the solar irradiance for every month directly impacts the mass flow steam rate, whose values fluctuated significantly, from a minimum value of 0.0048 kg/s in July, when the solar irradiance was the lowest, to 0.0093 kg/s for October, for the highest solar irradiance. The variation in the solar irradiance also affected the heat gained by the PTC collector in the range of 11,600 W to 22,700 W.

The total average length of the PTC for a 2″-diameter absorber was 27.17 m, as seen in Table 6. The saturated mass flow steam rate had a minimum of 0.0166 kg/s for July and a maximum of 0.0326 kg/s for October, while the solar irradiance had a lowest value for July (391.30 W/m^2) and the highest value for October (753.57 W/m^2). The heat gained was in the range of 40,600 W to 79,800 W.

Results for the 3″-diameter absorber are presented in Table 7. The steam mass flow rate was in the range from 0.0356 kg/s to 0.0702 kg/s for the months of July and October, respectively. The total average length of the PTC was 39.76 m. The minimal heat gained was for July with 46,500 W and the maximum heat gained had a value of 91,800 W for October.

The number of PTC collectors and the total aperture area to supply the steam to the CCPT can be determined for every simulated case, considering that the power plant operates with 20.594 kg/s of steam. The lowest and highest steam mass flows computed in the simulation were used to compute the number of PTC collectors to generate the steam, and the total aperture area was computed by the multiplication of the number of PTCs and the aperture in Table 3 for each absorber diameter. Table 8 shows this combination of parameters, in order to correctly size the solar field.

Table 8. The necessary PTC collectors and total aperture area for each study case.

Absorber Tube Diameter (Inches)	Mass Flow (kg/s)		Number of PTC Collectors		Total Aperture Area (Hectares)	
	Minimal	Highest	Minimal	Highest	Minimal	Highest
1	0.0048	0.0093	4290	2214	19.172	9.896
2	0.0166	0.0326	2140	632	19.450	9.903
3	0.0356	0.0702	579	294	19.515	9.897

As can be observed from Table 8, the number of collectors needed decreased as the diameter collector increased. However, the total aperture area remained almost constant, averaging values of 19.379 hectares for the month with the lowest solar irradiance and 9.989 hectares for the month with the highest solar irradiance value. According to the results in Table 8, the total area for the solar field remained almost the same for the geometrical proposals, however, the size of each PTC and its cost were significantly different. Obviously, less PTC are needed for a 3-in absorber, but its size is significantly bigger as is its cost and maintenance.

The mass flow steam rate is the main parameter of the PTC collector design, as explained previously, the mass flow directly depends on the solar irradiance reaching the collector, which is the reason why it is imperative to use a good flow control system due to the solar irradiance variation every day and in every season of the year, and even more if the exit temperature must be maintained as constant. Figure 4 shows the computed mass flow rate for the absorber diameters studied. The mass flow rate increases as the diameter of the absorber tube is augmented. Minimal values of the mass flow steam rate were shown for the 1″ diameter absorber and the highest values were for the 3″ diameter absorber. Additionally, it was observed that in the months with less solar irradiance, the mass flow decreased to maintain the needed energy power for the plant. For the month with the highest solar irradiance, the mass flow steam rate had the maximum value.

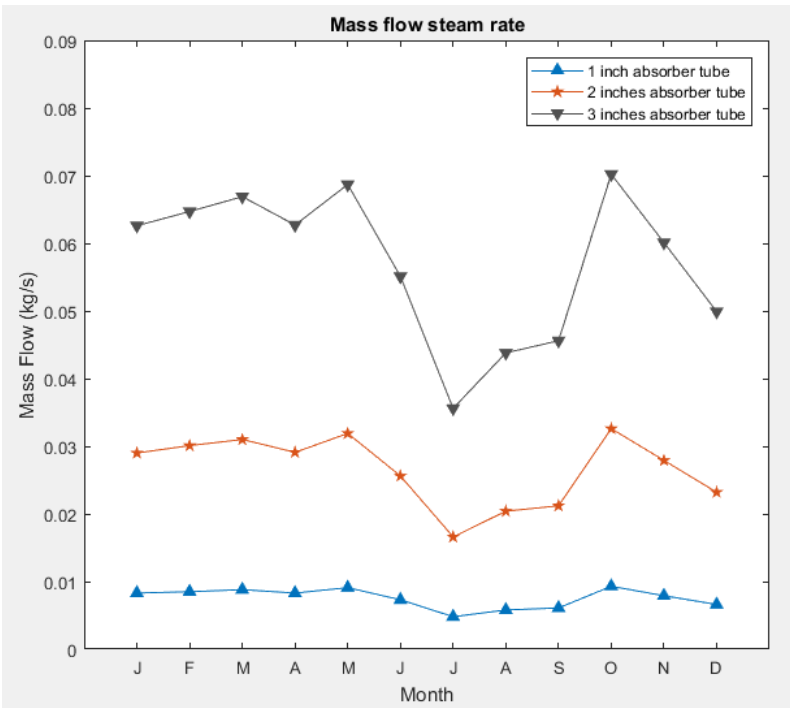

Figure 4. Mass flow steam rate for the absorber diameters studied.

A comparison of the total length for the absorber diameters analyzed is presented in Figure 5. The total length was almost constant throughout the year for each diameter absorber. The largest length was required for the 3″ absorber diameter while the shortest length for the 1″ absorber diameter. As the diameter in the absorber increased, a higher amount of heat gained was presented. In this sense, a bigger absorber will concentrate more energy and a considerable reduction in the number of concentrators will be required to reach the required power in the steam.

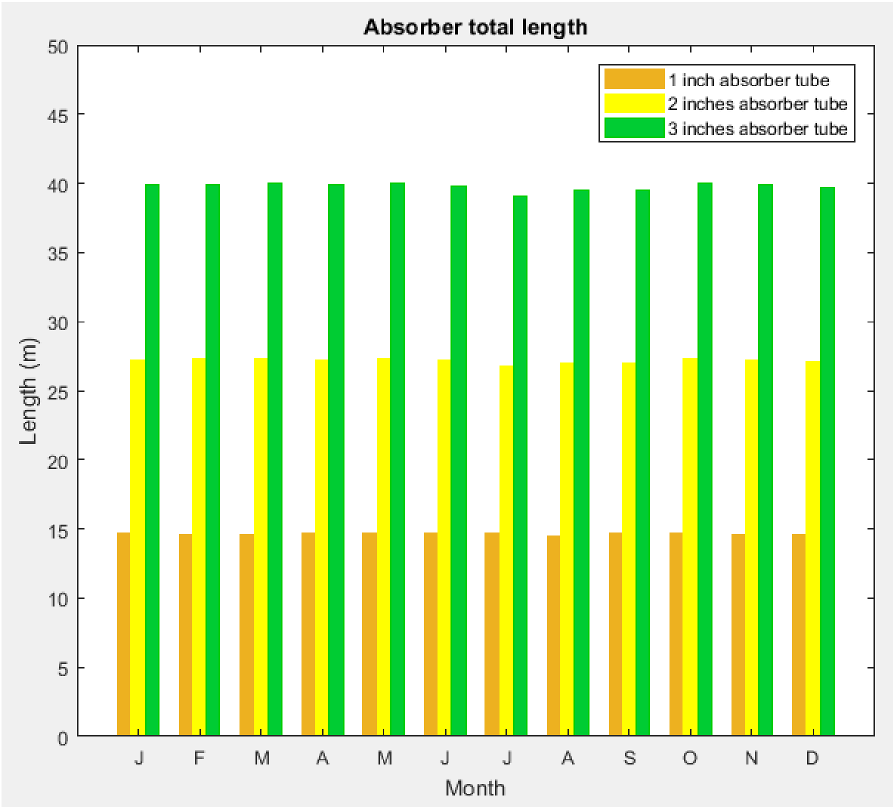

Figure 5. The total length of the absorber for the diameters studied.

The results show that by using the DSG system in once-through mode, the solar field area necessary to satisfy the saturated steam diminished significantly. The actual PTC collector solar field, installed in the combined cycle power plant Agua Prieta II has a total solar field aperture of 30 hectares, and if the lowest value of solar irradiance is considered as the design point when using the DSG system, the total solar field aperture was 19.379 hectares, which means that the aperture surface decreased by 35.4%. Aside from the decrease in the total installed solar field area, another important advantage of using a DSG system is that the use of heat exchangers is not necessary, reducing the installation costs.

Finally, the objective to prove the feasibility of modifying the Agua Prieta II plant was presented by means of the SOLEEC software application, which evaluated three different geometric combinations that satisfy the necessary power requirements. To make decisions as to whether to improve the plant, more detailed analyses will be required including economic analyses. However, the results shown here can serve as a starting point, thus demonstrating that the SOLEEC software meets the requirements of precision, accuracy, easiness, versatility, and reliability for the analysis of ISCC-PTC-DSG power plants.

6. Conclusions

The present work describes the feasibility of implementing parabolic trough solar collectors with a direct steam generation system in a combined cycle power plant 171 CC

Agua Prieta II in the north of Mexico, where the desert climate shows an abundant solar irradiance, making the place an excellent option to leverage solar resources.

The thermal analysis obtained by means of the SOLEEC software provided a comparison between a solar power plant implemented in the combined cycle power plant Agua Prieta II and the proposed PTC solar field using a DSG system in once-through mode. Three kinds of PTC designs were analyzed based on the absorber tube diameter for a saturated steam demand of 20.594 kg/s. All three design proposals satisfied the steam demand, and the results showed that the total aperture area of the solar field was almost constant, having values of 19.379 hectares for the month with the lowest solar irradiance and 9.989 hectares for the month with the highest solar irradiance.

The total aperture area was reduced by 35.4% with the DSG system compared to the actual installed solar field in the CCPT Agua Prieta. Aside from the reduction in the total installed area of the solar field, by using the DSG system, the installation of a heat exchanger is not necessary as the saturated steam is directly produced, reducing the complexity, the installation costs, and the total size.

The use of solar irradiance to produce steam does not generate any kind of exhaust gases that contribute to the greenhouse effect, so in this way, the solar field proposed by the SOLEEC software contributes to diminishing global warming. The numerical tool designed is an excellent tool for evaluating and designing a DSG system with high accuracy.

Author Contributions: E.E.C. and J.G.B.S. contributed in the SOLEEC software design, considering the correct implementation of the used mathematical models, to determine the correct geometrical parameters for the PTC collector, the optical efficiency, and the software validation using different experimental or simulated published data. J.d.l.C.A. designed the graphic interfaces for the SOLEEC software main menu and the direct steam generation software application. J.A.J.B. realized the thermal analysis for the preheating section considering monophasic flow. C.D.C.G.T. and M.B.A.V. analyzed the two phase flow phenomenon at the second stage of the absorber tube where the evaporation process was carried out. All authors contributed to the paper redaction and revision. All authors have read and agreed to the published version of the manuscript.

Funding: This research received no external funding.

Conflicts of Interest: The authors declare no conflict of interest.

References

1. Kabir, E.; Kumar, P.; Kumar, S.; Adelodum, A.A.; Hyum Kim, K. Solar Energy: Potential and future prospects. *Renew. Sustain. Energy Rev.* **2018**, *82*, 894–900. [CrossRef]
2. Shituu, S.; Li, G.; Zhao, X.; Ma, X.; Akhlaghi, Y.G. Review of thermoelectric geometry and structure optimization for performance enhancement. *Appl. Energy* **2020**, *268*, 115075. [CrossRef]
3. Garud, K.S.; Lee, M.Y. Thermodynamic, environmental and economic analyses of photovoltaic/termal-thermoelectric generator system using single and hybrid particle nanofluids. *Energy* **2022**, *255*, 124515. [CrossRef]
4. Elmohlawy, A.E.; Ochkov, V.F.; Kazandzhan, B.I. Study and prediction the performance of an Integrated Solar Combined Cycle Power Plant. *Energy Procedia* **2019**, *156*, 72–78. [CrossRef]
5. Achour, L.; Bouharkat, M.; Behar, O. Performance assessment of a integrated solar combined cycle in the southern of Algeria. *Energy Rep.* **2018**, *4*, 207–217. [CrossRef]
6. Sharma, C.; Sharma, A.K.; Mullick, S.C.; Kandpal, T.C. A study of the effect of designing parameters on the performance of linear solar concentrator based thermal power plants in India. *Renew. Energy* **2016**, *87*, 666–975. [CrossRef]
7. Abdel Dayem, A.M.; Nabil Matwally, M.; Alghamdi, A.S.; Marzouk, E.M. Numerical simulation and experimental validation of Integrated Solar Combined Power Plant. *Energy Procedia* **2014**, *50*, 290–305. [CrossRef]
8. Bahari, M.; Ahmadi, A.; Dashti, R. Exergo-economic analysis and optimization of a combined solar collector with steam and Organic Rankine Cycle using particle swarm optimization (PSO) algorithm. *Clean. Eng. Technol.* **2021**, *4*, 100221. [CrossRef]
9. Teleszewski, A.T.; Zukowski, M.; Krawczyk, D.A.; Rodero, A. Analysis of the Applicability of the Parabolic Trough Solar Thermal Power Plants in the Locations with a Temperate Climate. *Energies* **2021**, *14*, 3003. [CrossRef]
10. Alotaibi, S.; Alotaibi, F.; Ibrahim, O.M. Solar-assisted steam power plant retrofitted with regenerative system using Parabolic Trough Solar Collectors. *Energy Rep.* **2020**, *6*, 124–133. [CrossRef]
11. Kalogirou, S. *Solar Energy Engineering Processes and Systems*; Elsevier Inc.: New York, NY, USA, 2009.
12. Eck, M.; Hirsch, T. Dynamics and control of parabolic trough collector loops with direct steam generation. *Sol. Energy* **2007**, *81*, 268–279. [CrossRef]

13. Kandlikar, S.; Masahiro, S.; Dhir, V. *Handbook of Phase Change, Boiling and Condensation*; Taylor and Francis: New York, NY, USA, 1999; pp. 368–399.
14. Incropera, F.; De Witt, D.; Bergman, T.; Lavine, A. *Fundamentals of Heat and Mass Transfer*, 6th ed.; John Wiley and Sons: New York, NY, USA, 2007; pp. 505–518.
15. Baehr, H.; Stephan, K. *Heat and Mass Transfer*, 2nd ed.; Springer: Berlin/Heidelberg, Germany, 2006; p. 475.
16. Chen, J.C. Correlation for boiling heat tranfer to saturated fluids in convective flow. *Ind. Eng. Chem. Process Des. Dev.* **1966**, *5*, 322–329. [CrossRef]
17. Gunger, K.; Winterton, R. Simplified general correlation for saturated flow boiling and comparisons of correlations with data. *Can. J. Chem. Eng.* **1987**, *65*, 148–156.
18. Liu, Z.; Winterton, R.H.S. A general correlation for saturated and subcooled flow boiling in tubes and annuli base on nucleate pool boiling. *Int. J. Heat and Mass Transf.* **1991**, *34*, 2759–2765. [CrossRef]
19. Odeh, S.; Morrison, G.; Behnia, M. Modelling of parabolic trough direct steam generation solar collectors. *Sol. Energy* **1998**, *62*, 395–406. [CrossRef]
20. Enciso Contreras, E.; Barbosa Saldaña, J.G.; Jimenez Bernal, J.A.; Gutiérrez Torres, C.C. The development of software SOLEEC for parabolic trough solar collector designing. *New Approaches Eng. Res.* **2021**, *2*, 111–123.
21. Enciso, C.E.; Barbosa, S.J.G.; Jiménez, B.J.A.; Del Carmen, G.T.C.; Quinto, D.P. Software SOLEEC designing parabolic through solar collectors with direct steam generation system. *DYNA* **2018**, *93*, 89–95. [CrossRef]
22. Enciso, C.E.; Barbosa, S.J.G.; Mora, O.A.; Bonilla, B.W.C.; Salazar, P.M.; Aguilar, A.J.A.; Duran, M.P. Analysis and design of an integrated solar combined cycle power plant using the software SOLEEC. *J. Renew. Sustain. Energy* **2018**, *10*, 053704. [CrossRef]
23. Semarnat-CFE. Available online: https://apps1.semarnat.gob.mx:8443/dgiraDocs/documentos/son/estudios/2006/26SO2006E0013.pdf (accessed on 11 December 2022).