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Optical performance assessment of a handmade prototype of linear Fresnel concentrator

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ABSTRACT

This article aims to evaluate the optical behavior of a small handmade prototype of a linear Fresnel concentrator (LFC). The system was developed and tested as a water heater and steam generator at the Unidades Tecnológicas de Santander university, located in Bucaramanga, Colombia. Optical factors of the thermo-solar system studied were taken into account, such as concentration ratio and optical efficiency relationships. The Monte Carlo ray tracing method (MCRT) was carried out as an optical evaluation tool through the application of the free access software "SolTrace" and "TONATIUH" to later contrast the results obtained with both simulation tools. At the same time, the performance output from the simulations was compared with the optical performance of the experiments previously carried out with the device LFC, with the aim of evaluating the reliability and accuracy of the analysis developed through the MCRT methodology. The results obtained showed that the number of reflective mirrors or area of reflection has a direct impact on the optical efficiency of the prototype, where it is evidenced that there is a higher optical efficiency and a higher CR when the reflection area is larger. Similarly, direct solar radiation (DNI) has the same trend, showing that higher levels of direct solar radiation (DNI) increase optical efficiency. Finally, it was observed that the variation in the number of rays used in the simulations (10,000,000 and 5,000,000) does not influence the optical performance of the device.

Keywords: Performance, Linear Fresnel Reflector, Ray Tracing, Renewable, Concentrator

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1. Introduction

CSP systems have taken off in the last decades due to the development of different technologies [1], amongst them, the following four are the most widely spread: parabolic cylindrical collector (PTC), Linear Fresnel concentrator (LFC), solar tower and Stirling parabolic disk [2] [3] [4]. Even though they differ in the design, all of them share a common characteristic: "The application of reflective mirrors"[5] [6]. Mirrors are an important component in the operation of systems, because they are responsible for reflecting and concentrating direct solar radiation at a specific receiver. [7]. A control system ensures that the mirrors follow the path of the sun during the day, guaranteeing the reflection of solar radiation that made the point of concentration [7] [8].

Specifically, this paper deals with LFC systems, which are made up of long rows of flat or slightly curved mirrors that reflect the sun's rays into a linear receiver [9] [10]. Amongst the four CSP technologies, LFC is considered as the technology with the greatest potential for research and technological development [11] [12].

Even though it is the system showing the lowest optical and thermal efficiencies [13], they present several advantages: (a) the mirrors used in their design are narrow and easy to manufacture, (b)their support structure is light, (c) the effect of the wind is negligible, (d) they require less land, (e) their manufacturing cost It is lower and they it allows the inclusion of local work in their operation and maintenance. All these features prove its potential for its development and implementation in the medium and long term [14] [15].

The analysis of the optical performance of CSP systems is a major problem that it is not easy to deal with, especially due to the variation in the quantity and quality of the heat flux that is concentrated in the receiver. [16] [1]. Thus, it should be understood as a fundamental parameter for the general efficiency of the systems as well as their development at a technological level, directly affecting their application worldwide. [17]. Optical analysis in CSP systems and specifically of a LFC system, can be developed through three methods: numerical simulation, computational fluid dynamics (CFD modeling) and Monte Carlo Ray Tracing (MCRT)[1]. These methods allow the analysis of optical models in order to determine the performance of the design point of the system, as well as to modify its angles of incidence to evaluate its behavior in any position of the sun during a typical meteorological year [18] [19].

For its part, there are several studies in the literature covering numerical simulation . In 2015, Moghimi et al. introduced a finite volume (FV) method that combined optical and thermal modeling [20]. The same year, Hongn et al. developed a least squares method for the calculation of a final loss factor of a CFL to be multiplied by the Incidence Angle Modifier (IAM) [21]. Finally, Bellos and Tzivandis developed equations that determine modifying coefficients of the IAM of the collectors [22]. In the case of the computational fluid dynamics (CFD) application, Heimsath et al. investigated the losses of a receiver tube through the application of a CFD model together with a ray tracing code [23].

The Monte Carlo Ray Tracing (MCRT) method has been proven to be a flexible, efficient and powerful method for conducting LFC system simulations, as it is able to accurately maintain geometric configurations, materials and optical properties, random optical errors and operating conditions [24] [25]. In 2016, Qui et al. developed a model that determines the optical and thermal behavior of a LFC system combining the finite volume method (FVM) and the MCRT method. [26]. In turn, Cheng et al. developed a new model of optical optimization for LFC systems using the particle swarm optimization (PSO) algorithm and the MCRT method [27].

As a result, specific optical evaluation codes have been developed applying the MCRT methodology, some of them being freely available. Amongst them, some of the most relevant are the following [28]: SOLTRACE [29], TONATIUH [30], MIRVAL [31], SOLERGY (32)(Stoddard et al., 2009)(Stoddard et al., 2009) [32], SAM [33], ASAP, DELSOL [34] , among others [35] [36]. Consequently, some authors have evaluated systems applying several of the tool mentioned above, for example, Jafrancesco et al, presented a comparison of different optical simulation tools, applying two open access software for the development; SOLTRACE y TONATIUH, for its great application at an industrial level and two commercial software (TracePro y CRSA-2) [28]. Later, Delgado Carreño highlighted the simplicity and reliability of the SolTrace and TONATIUH software to optically evaluate this type of LFC concentrators [37].

This paper deals with the experimental evaluation of the optical performance of a LFC artisan prototype developed in the Unidades Tecnológicas de Santander university in Bucaramanga, Colombia [15] [8]. The concentration relationship and the optical efficiency of the LFC prototype were assessed using the MCRT method, specifically, through the application of the SolTrace Software developed by the National Renewable Energy Laboratory (NREL) [29] and the TONATIUH Software developed by the National Center for Renewable Energies (CENER) [30]. Both tools allow the modeling of LFC systems and therefore, the assessment of their optical performance, providing information on the behavior of the system. The results from both analyses are compared in terms of the optical behavior. Finally, experimental results were compared with the theoretical results obtained from the simulations.

2. Material and methods

2.1. LFC prototype

The LFC handcrafted prototype manufactured for the experimental process was designed with the aim of warming water up, generating vapour. The prototype was built and installedat the Unidades Tecnológicas de Santander university in Bucaramanga, Colombia [15] [8], as it is presented in Figure 1. The built prototype is based on four main components:

- Reflectors or mirrors
- Receiver tubes
- Trapezoidal cavity. It serves as a second reflector- Galvanized Sheet 20 Gauge, Length 1.2 m, height 0.035 m and 0.12 m wide. Includes clear glass to reduce heat transfer losses.
- Preheating system (Coil - Provides temperatures to the collector inlet in a range of 30 to 60 ° C- Diameter 0.00635 m, 18 tubes in parallel, Aluminum)

In addition to the main components, the current LFC prototype used auxiliary systems for the experimentation stage; a data acquisition system, pumping system and solar tracking system (see Figure 1).

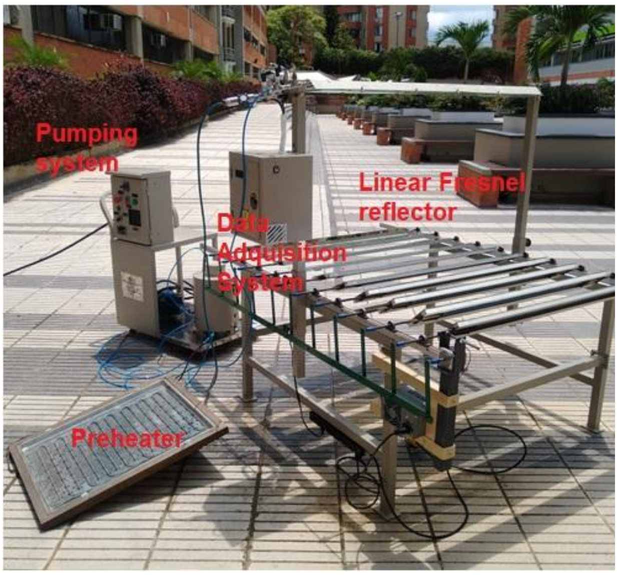


Figure 1. LFC Artisan prototype with auxiliary systems for experimentation

The dimensions of the prototype are shown in Table 1. In previous work, an experimental assessment was carried out on this device, showing an optical performance under hydro-static of the 15 % and hydro-dynamic [15] of the 7,19% conditions [8].

Table 1. Dimensions of the components of the LFC Artisan prototype

Component	Dimension
Total number of reflective mirrors	10
Mirror Length (L_m)	1 m
Mirror width (W)	0.1 m
Number of absorber tubes	2
Receiver Tube Diameter "Outer" ($D_{A,ext}$)	0.003175 m
Receiver Tube Diameter "Inner" ($D_{A,int}$)	0.0004699 m
Absorbent tubes length	1.2 m
Focal distance (F)	0.75 m

The optical characteristics of the components are listed in Table 2. These properties are required for the development of the optical model of the device, being inputs for the SolTrace and TONATIUH software packages. The use of these software's will allow to evaluate the flow of calor and this exact distribution on the surface of the receiver tube and the reflective mirrors.

Table 2. Optical Characteristics of the Reflection System LFC Artisan Prototype

Component	Dimension
Solar absorptance factor of copper pipes (α)	0.8
Reflectance of the mirrors (ρ_m)	0.85
Emissivity of the absorber tube (ε_{Ab})	0.12

2.2. Optical model

The evaluation of the optical and thermal performance of the Fresnel linear concentration or reflection systems requires high precision mathematical models based on predictions from which the optical coefficients can be determined and analyzed. Determining the optical efficiency of LFC systems must be carried out with accuracy and precision due to the relationship between various factors, among which the following significantly stand out: influence of the angle of incidence, errors of the radiation reflector, losses due to shading and ratio or ratio. concentration.

Consequently, the optical models used to determine the intensity and distribution of the thermal flux on the surface of the concentration tubes and the reflection mirrors, according to a controlled number of solar rays and direct normal irradiance (DNI). Additionally, geometric engineering dimensions of the real prototype components were included.

This optical analysis will depend on the application of two free access programs to determine the optical behavior of the prototype, the two tools are:

- SolTrace (Download https://www.nrel.gov/csp/soltrace-download.html) is based on the MCRT methodology, through a C++ code with multi-threading capability. Requires the use of a plugin with Google Sketchup software, to obtain the geographic coordinates and geometry of the LFC system to be modeled (The software allows to create directly the geometry in its graphical work interface). Allowing to evaluate the distribution of the thermal flux product of the solar radiation absorbed by the tubes and reflected by the mirrors. SolTrace has comprehensive and intuitive Post-Processing capabilities, allowing the visualization of rays and intersection points, as well as the automatic calculation of flow intensity values, additionally it can be exported as a CSV file for later editing [28].
- TONATIUH (Download https://iat-cener.github.io/tonatiuh/) is based on the MCRT method and is written in C++ programming language as multi-platform software with parallelization of CPU. The graphical interface allows creating the geometry of the system and the geographic coordinates of the modeling. Allowing to evaluate the distribution of the thermal flux product of the solar radiation absorbed by the tubes and reflected by the mirrors.

The architecture of TONATIUH allows the use of plug-ins to extend the functions in a simple way, allowing the simulation of centralized and complex CSP systems, using data supplied by the user such as a CAD file and a tool to calculate flow distributions [28].

The simulations in SolTrace and in TONATIUH will be developed by varying the value of direct solar radiation "DNI (W/m^2)" and the number of rays, in different scenarios in order to compare the two tools used and determine the ratio or concentration ratio and the optical efficiency of the device.

Table *3* shows the two variants of DNI to be used in the simulations. These values were based on measurements previously made, through the use of a DNI TED 132 Power Solar Meter measuring instrument during February and March 2021, where the average was 600 W⁄m ^ 2 at 12 m. The S2 value was included, based on a study of the behavior of DNI in the place of experimentation of the system in 2019 where the average of DNI in the test time was 350 W⁄m ^ 2 [38].

Table 3. DNI Data for the Two Comparison Scenarios

	S1	S2
DNI (W/m^2)	600	350

In turn, each of the chosen scenarios (S1 and S2) is evaluated by means of simulation with different numbers of rays launched. These values were determined based on the recommendations of software developers, where they stand out: "the greater the number of employer rays in the simulation process, the more accurate the results of the simulation process will have".

Table 4. Number of Solar Rays Used in the Simulation

	SOLTRACE	TONATIUH
Desired number of ray intersections	5.000.000 / 10.000.000	5.000.000 / 10.000.000

Finally, Figure 2 shows the three configurations to be evaluated for each of the DNI variation scenarios presented in Table *3* and for each of the desired number of intersections of rays presented in Table *4*. The reflection area will be modified Starting with the analysis of the original experimental configuration of 10 mirrors (area 1 m ^ 2) (See Figure 2 a), later a configuration with 8 mirrors (area 0.8 m ^ 2) (See Figure 2 b) and 6 mirrors will be studied. (Area 0.6 m ^ 2) (See **Error! Reference source not found.** c). This process aims to determine the influence of the reflection area, the number of rays and the DNI, on the performance of the system, calculating the concentration ratio or ratio (CR) and the optical efficiency.

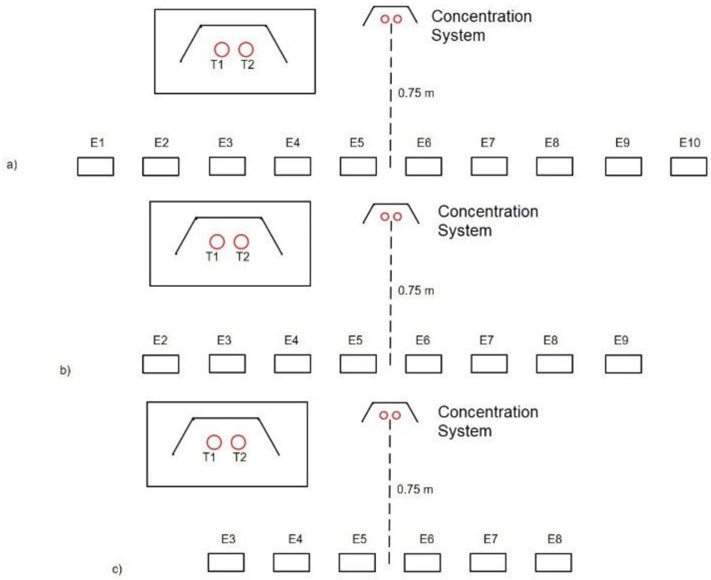


Figure 2. Configuration Of the mirror for the development of the simulations applying SolTrace and TONATIUH

On the other hand, the optical performance of the LFC artisan prototype can be calculated by applying equation 1.

$$\eta_{spp} = \eta_{sf} * \eta_{rec} * \eta_{pb} \quad (1)$$

η_{spp} = efficiency of the Fresnel system or solar plant
η_{sf} = mirror field efficiency
η_{rec} = receiver performance
η_{pb} = power block Efficiency
The variation of the performance of the Fresnel system will be determined from the optical performance of the field of Mirrors (See equation 2). The performance of the receiver and the power block remain constant for the present analysis.

$$\eta_{sf} = \frac{Q^* A_{rec}}{DNI^* A_{sf}} \quad (2)$$

Q = mean flux generated by the mirror field
A_{rec} = area of receiver tube
A_{sf} = area of the primary reflector field
DNI = direct normal radiation or direct solar radiation
The value of Q for the case studies in this document will be determined from the maximum intensity flux of each of the mirrors of the Fresnel system, these data will be provided by the results of the simulation process applying the SolTrace and TONATIUH tools.
Finally, to determine another important optical characteristic known as the concentration ratio (CR), the equation is applied:

$$CR = \frac{\text{Number of rays concentrated on the receiver}}{\text{Number of rays reflected by the total area of the reflector}} \quad (3)$$

2.3. SolTrace modeling

In this section, the simulations process is carried out using the SolTrace tool to evaluate the optical performance of the linear Fresnel concentrator, analyzing the distribution of the thermal flux intensity of the solar radiation reflected by the mirrors and concentrated by the absorber tubes.

SolTrace estimates the distributed heat flux at the level of the receiver tubes by applying the MCRT method, based on mathematical probability models, widely used to evaluate the behavior of CSP. Additionally, the MCRT method adapts to complex geometries, evaluating the exact ray tracing of reflection, refraction and transmission, from the release of a determined number of rays and a specific DNI.
The simulation process in SolTrace is done in stages. The first step is to determine the geometry of the system in coordinates that are read by the software code, for this process, a tool called Google Sketchup 8 is used, which allows the handmade Fresnel prototype to be modeled on a 3D plane as shown in Figure 3. Once the 3D LFC model has been developed, the file is saved in .stinput format, which is compatible and allows integration with SolTrace.

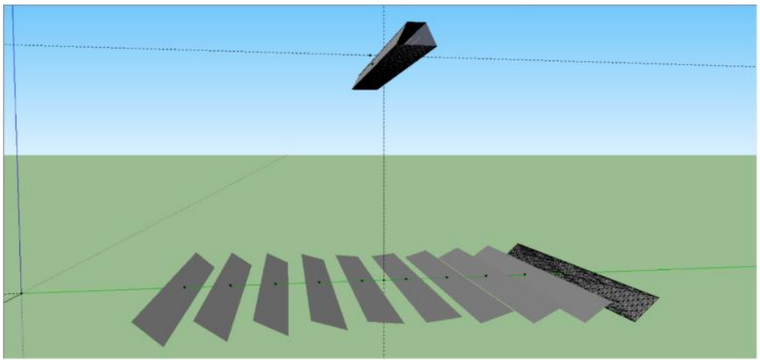
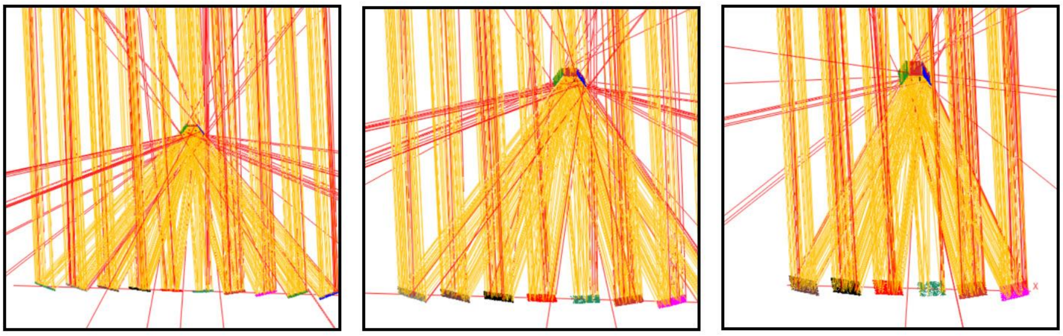


Figure 3. 3D modeling LFC craft prototype in google sketchup 8

Subsequently, the .stinput file created with Google sketchup 8 is opened in SolTrace and automatically loads the system components in the graphical interface of the tool. Then, the shape and direction of the sun is defined (Hour 12 m), followed by the creation and assignment of the optical properties for the reflecting mirrors and absorbent tubes. Finally, the DNI and the number of rays used in the simulation process are defined (See Figure 4). Once the system has been fully defined, it is saved and the simulation process begins. Additionally, SolTrace evaluates refraction and reflection at each system interface using the information provided.



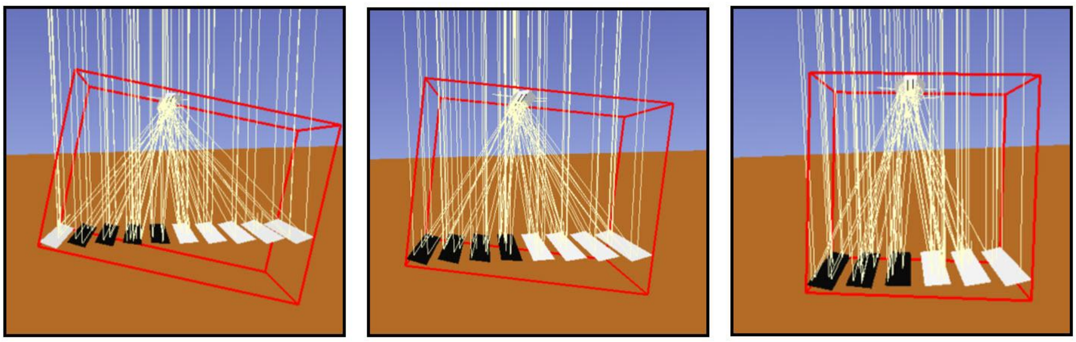
a) 10 mirrors b) 8 mirrors c) 6 mirrors

Figure 4. Ray tracing in SolTrace with 10, 8 and 6 mirrors

2.4. TONATIUH modeling

The simulation process in TONATIUH is also based on the MCRT methodology and is carried out under the same optical characteristics, geometric dimensions (area of reflection), DNI and number of rays as with the SolTrace tool, analyzing the distribution of thermal flux intensity. of the solar radiation reflected by the mirrors and concentrated by the absorber tubes.

The simulation process with the TONATIUH tool is also developed in stages. Starting with the definition of the position of the sun in the sky, a process for which a free access web tool known as Sun Eart Tools (https://www.sunearthtools.com/) is used. The time you select to determine the location of the sun, is the same as in the SolTrace simulations (Hour 12 m). Subsequently, the atmosphere to be used is defined and the geometry of the LFC artisan prototype is defined manually, in the X, Y and Z axes. Next, the optical characteristics of reflection and refraction of each component of the device are defined, as well as the DNI and the number of rays. Finally, the simulations are saved and run (See Figure 5).



a) 10 mirrors b) 8 mirrors c) 6 mirrors

Figure 5. Ray Tracing in TONATIUH with 10, 8 and 6 mirrors

3. Results and discussion

The LFC reflector studied is simple, easy and decentralized, made up of 10 planar mirrors arranged in parallel that are tilted by means of a solar tracking system in order to reflect solar radiation to the focal point, the latter made up of two tubes.

After analyzing the results of the simulations carried out in SolTrace, Figure 6 shows a graph that relates the results of the CR value that were determined by applying equation 3, where the trend in concentration ratio percentages is maintained during the variation of DNI and ray intensity for a fixed number of mirrors.

The percent concentration ratio (CR) is directly affected by the size of the reflection area. In the present case study, in the simulations with a reflection area of 1 m ^ 2 (10 mirrors) it presents a value greater than 24% with respect to the reflection area of 0.8 m ^ 2 (8 mirrors) and a value greater than 35% with respect to the reflection area of 0.6 m ^ 2 (6 mirrors).

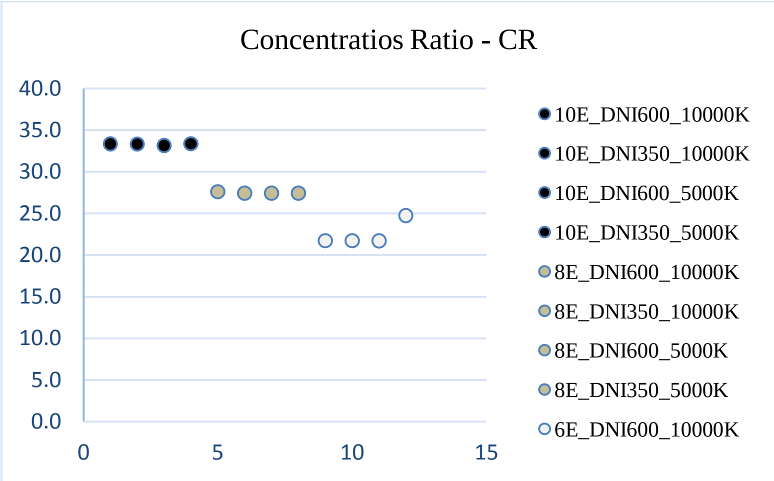


Figure 6. Comparison graph of the concentration ratio percentages in the simulations carried out with 10, 8 and 6 mirrors applying SolTrace

On the other hand, after evaluating the results of the simulations carried out in TONATIUH, Figure 7 shows a graph that relates the results of the CR value that were determined by applying equation 3, where the trend of the results is similar to those obtained by the SolTrace tool and the concentration ratio (CR) percentage is directly affected by the size of the reflection area.

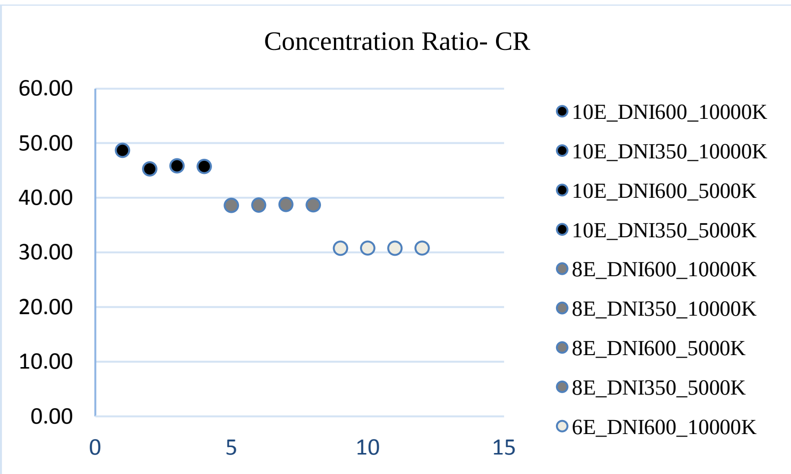


Figure 7. Graph comparison of the concentration ratio percentages in the simulations carried out with 10, 8 and 6 mirrors applying TONATIUH

In turn, the results of Table 5 show the comparison of the concentration ratio averages of the 4 evaluated scenarios. On the one hand, SolTrace has lower levels of CR with respect to TONATIUH, but the trend in variation is maintained for both when starting from the experimental reflection area of 10 Mirrors, to the modified areas with 8 and 9 Mirrors, this is due to, to the characteristics of each software.
Additionally, Figure 8 shows a graphical representation of the behavior of the data presented in Table 5 and concludes that:

- When comparing the results of the simulations through the SolTrace and TONATIUH tools, it was found that there is a relationship in the results shown in Table 5.
- When the intensity or value of direct solar radiation (DNI) increases, the concentration ratio at the surface of the receiver increases.
- As the area of reflection or the number of reflective mirrors increases, the concentration ratio at the surface of the receiver increases.

Table 5. Average concentration ratio comparison

Concentration Ratio (CR)					
		SOLTRACE		TONATIUH	
Reflective Mirrors Number	Reflection Area m^2	DNI 600 W/m^2	DNI 350 W/m^2	DNI 600 W/m^2	DNI 350 W/m^2
10	1	33,3	33,4	47,3	45,5
8	0,8	27,5	27,4	38,7	38,7
6	0,6	21,7	23,2	30,8	30,8

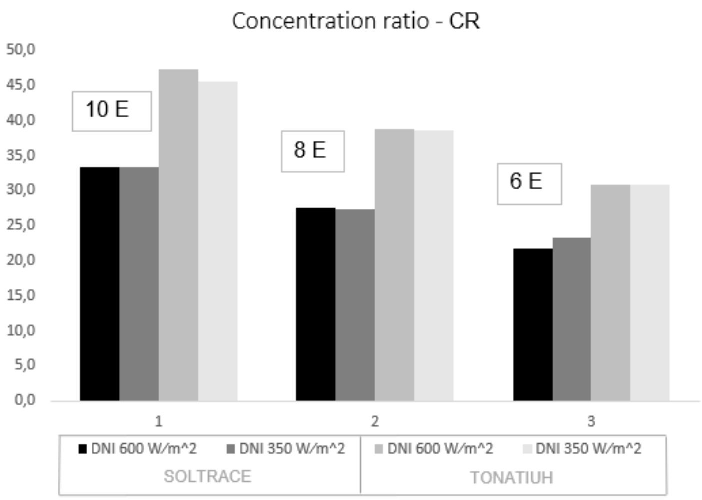


Figure 8.Trend of average concentration ratio between tools

Additionally, the results of 8 show the comparison of the variation of the average concentration ratio percentages based on the information presented in Table 6, taking as a starting point the values delivered in each of the 4 scenarios analyzed with a reflection area of 1 m ^ 2 (10 mirrors).
Finally, Figure 9 shows a graphic representation of the behavior of the CR variation percentages presented in 8 and concludes that:

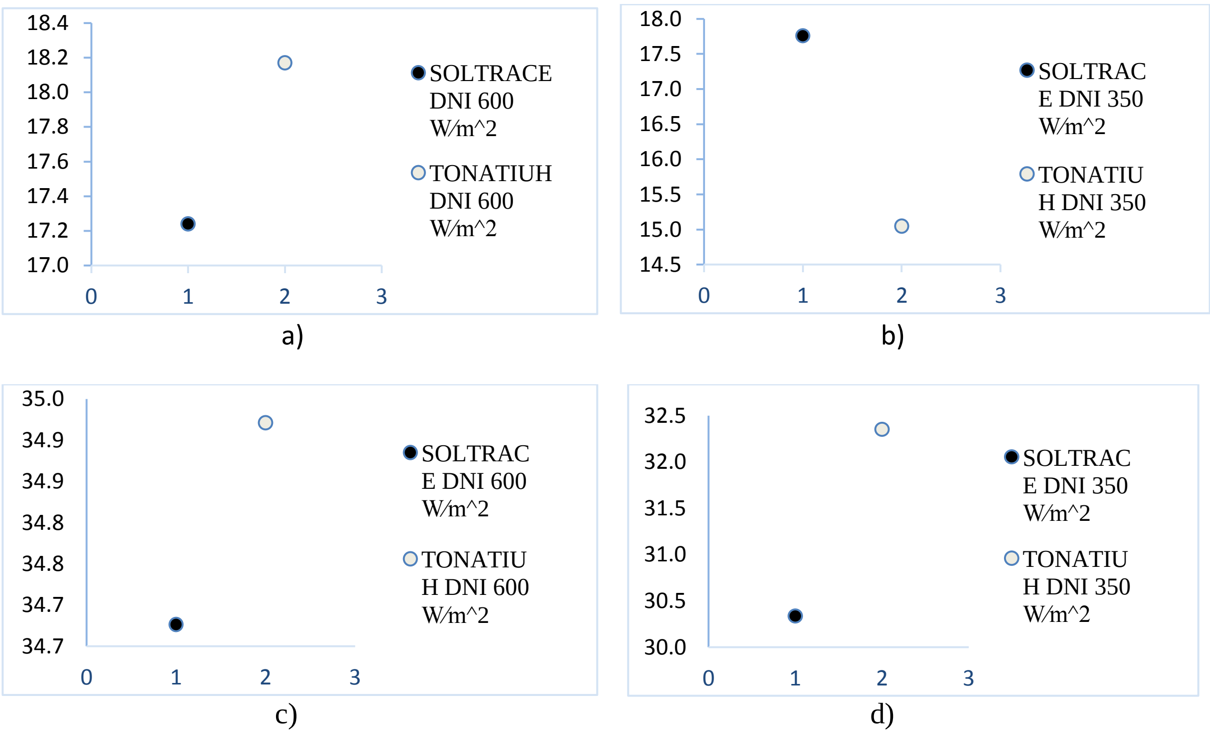
- There is a significant relationship between the percentages of difference in the scenarios evaluated by each tool (SolTrace-TONATIUH) after evaluating the results of the simulations. This confirms the accuracy of the results obtained through the application of the two Software, regardless of their differences in the own use of ray tracing algorithms under the Monte Carlo method.

- When the reflection area or number of mirrors decreases, the greater the decreasing variation of the CR percentage.
- **Error! Reference source not found.** "a" "b" "c" and "d" shows a trend of variation in percentages not exceeding 1% between the SolTrace and TONATIUH Software, confirming the relationship in the results obtained in the simulation processes developed.

Table 6. Average concentration ratio comparison

% Variation CR					
		SOLTRACE		TONATIUH	
Reflective Mirrors Number	Reflection Area m^2	DNI 600 W/m^2	DNI 350 W/m^2	DNI 600 W/m^2	DNI 350 W/m^2
10	1	0,0	0,0	0,0	0,0
8	0,8	17,2	17,8	18,2	15,1
6	0,6	34,7	30,3	34,9	32,4

Figure 9. Variation trend of the average concentration ratio percentages 8 and 6 mirrors



The optical efficiency of the configuration was developed by applying equation 2 and by means of the mean flow value generated by the mirror field (Q), supplied by each of the simulations. The Q value is supplied by each of the tools numerically and visually, as shown in Figure 10 corresponding to an intensity map applying SolTrace (See Figure 10 a) and TONATIUH (See Figure 10 b).

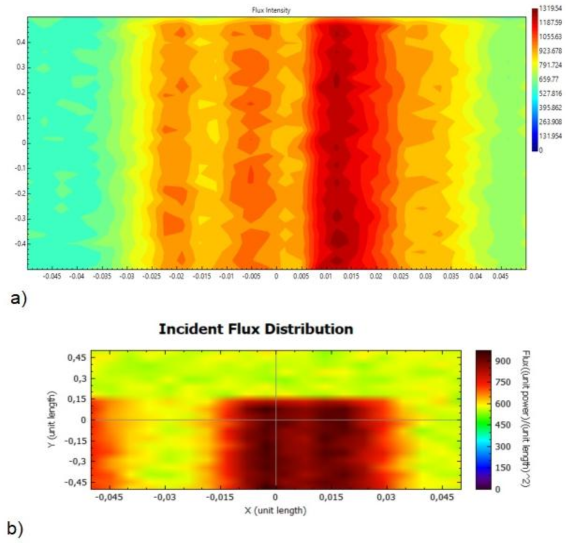


Figure 10. Mean flow maps generated by the mirror field (Q) applying SolTrace (A) and TONATIUH (B)

Table 7 shows the percentage (%) of optical efficiency of the system in each of the evaluated scenarios applying SolTrace and TONATIUH. On the other hand, Figure 11 shows a graphical representation of the behavior of the optical efficiency percentages determined by the evaluations carried out between the tools and concludes that:

- When the reflection area or number of mirrors decreases, the optical efficiency of the system is directly affected, that is: the greater the reflection area, the greater the optical efficiency of the system and the less the reflection area, the lower the optical efficiency of the system.

Table 7. Comparison of percentage values (%) of optical efficiency of the simulations applying SolTrace and TONATIUH

	10 Mirrors		8 Mirrors		6 Mirrors	
	DNI 600	DNI 350	DNI 600	DNI 350	DNI 600	DNI 350
SolTrace	6,37	3,72	5,08	3,14	3,82	2,23
TONATIUH	6,00	3,48	4,57	2,98	3,66	2,12

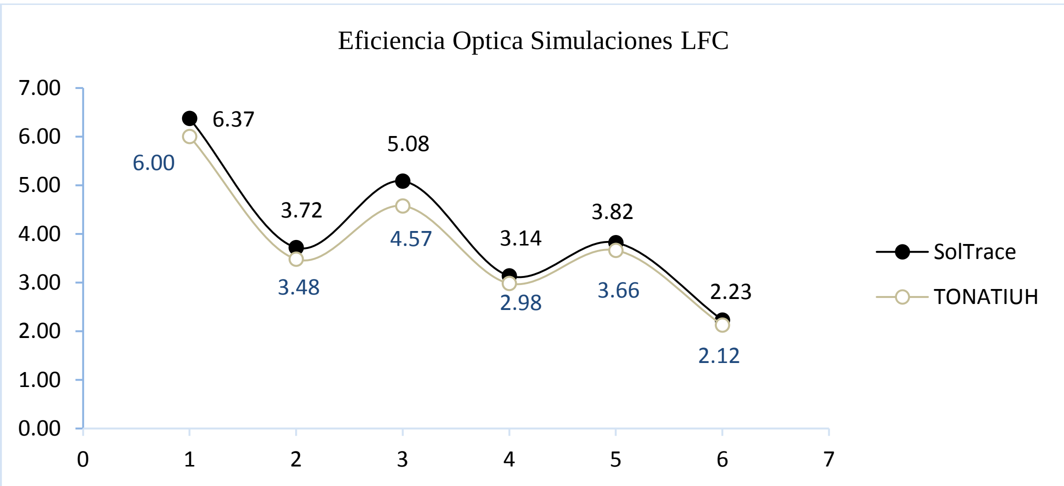


Figure 11. Comparative graph of the percentage values (%) of optical efficiency of the simulations applying SolTrace and TONATIUH

On the other hand, the real efficiency value of the LFC system, for the experimentation carried out during the year 2021, is η = 7.19%, a value presented in Table 8 together with the results previously presented in Table 7, relating and comparing the values simulated optical efficiency and actual value.
Consequently, Figure 12 shows a graphic representation of the relationship between the simulated optical efficiency values (applying SolTrace and TONATIUH) and the real value product of a previous experimentation and concludes that:

- There is a relationship between the real value of optical efficiency and the simulations applying SolTrace and TONATIUH. This confirms the accuracy of the results obtained through the application of the two Software, regardless of their differences in the own use of ray tracing algorithms under the Monte Carlo method. The real value was higher than the simulations, this is due to the variation of solar radiation during the test days and uncontrolled variables that intervene in the process such as: cloud cover, wind speed and direction, among others.

Table 8. Comparison difference of real optical efficiency of the systems and the simulations applying SolTrace and TONATIUH

	10 Mirrors		8 Mirrors		6 Mirrors	
	DNI 600	DNI 350	DNI 600	DNI 350	DNI 600	DNI 350
Experimentation			7.19			
SolTrace	6,37	3,72	5,08	3,14	3,82	2,23
TONATIUH	6,00	3,48	4,57	2,98	3,66	2,12

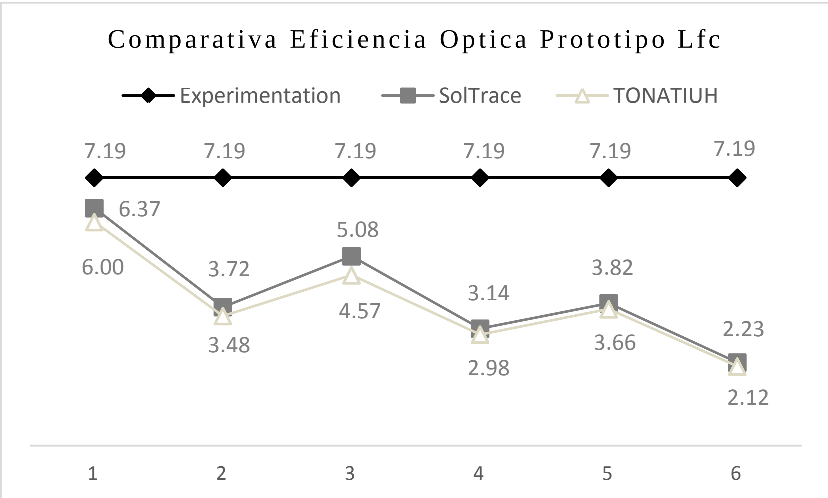


Figure 12. Comparative graph of the percentages of difference in the real optical efficiency of the system and the simulations applying SolTrace and TONATIUH

Additionally, Table 9 shows the percentages of difference between the real value of optical efficiency and each of the simulations developed. Additionally, Figure 13 shows a graphical representation of the data presented in Table 9 and concludes that:

- The Simulations carried out in SolTrace show difference percentages with respect to the real optical efficiency value, which vary from 11.36% in the best conditions, to 69% under the most unfavorable conditions. The simulations with DNI of 600 W / m ^ 2 present a lower percentage of difference than those developed with DNI of 350 W / m ^ 2. Additionally, there is a direct impact on the performance of the system, which is based on the fact that, the lower the DNI and the reflection area, the lower the optical efficiency of the system.

- The simulations carried out in TONATIUH show difference percentages with respect to the real optical efficiency value, which vary from 16.54% in the best conditions, to 71% under the most unfavorable conditions. The simulations with DNI of 600 W / m ^ 2 present a lower percentage of difference than those developed with DNI of 350 W / m ^ 2. Additionally, there is a direct impact on the performance of the system, which is based on the fact that, the lower the DNI and the reflection area, the lower the optical efficiency of the system.
- SolTrace shows in all the simulations values closer than 4% than the TONATIUH results, with respect to the real optical efficiency value.

Table 9. Comparison percentage of difference of real optical efficiency of the systems and the simulations applying SolTrace and TONATIUH

	10 Mirrors		8 Mirrors		6 Mirrors	
	DNI 600	DNI 350	DNI 600	DNI 350	DNI 600	DNI 350
Experimentation				0		
SolTrace	11,36	48,30	29,30	56,38	46,89	69,02
TONATIUH	16,54	51,61	36,40	58,55	49,09	70,45

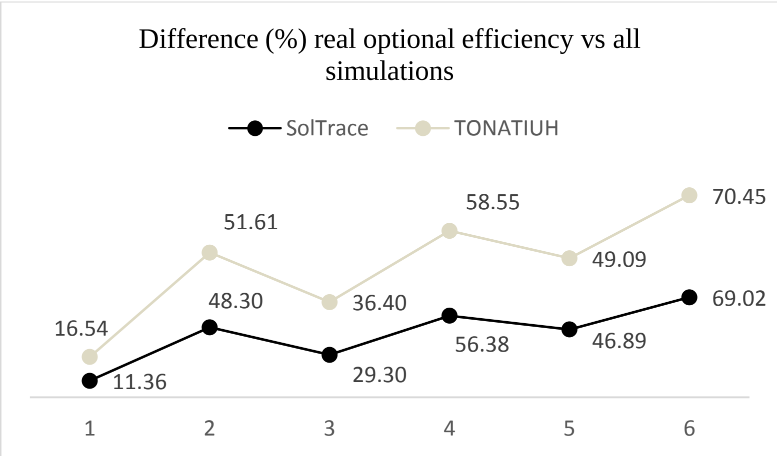


Figure 13.Comparative graph of the percentages of difference in the real optical efficiency of the system and the simulations applying SolTrace And TONATIUH

Finally, Table 10 shows the percentages of difference between the real value of optical efficiency and the simulations developed in SolTrace and TONATIUH, under the same conditions of the real system (10 mirrors, Area 1m ^ 2 and DNI 600 W / m ^ 2) . Additionally, Figure 14 shows a graphical representation of the data presented in Table 10 and concludes that the SolTrace tool presents results with greater precision than the real efficiency value of the system, while TONATIUH tends to be less precise. The differential in the values obtained between the two tools is 5.1%.

Table 10. Comparison of the Difference percentage of the real optical efficiency of the system and the simulations applying SolTrace And TONATIUH under the same DNI conditions

	10 mirrors DNI600	Δ% η
Experimentation	0	
SolTrace	11,36	
TONATIUH	16,54	5.1

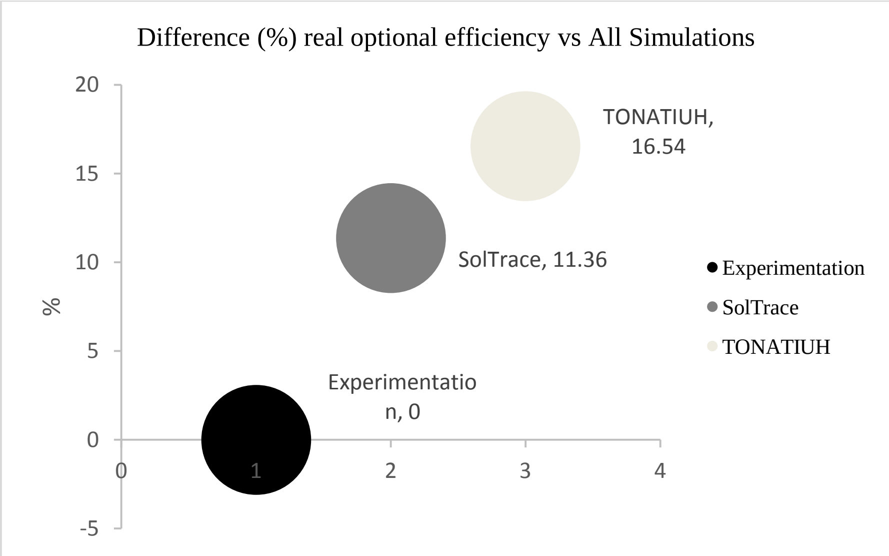


Figure 14. comparative graph of the percentages of difference in the real optical efficiency of the system and the simulations applying SolTrace and TONATIUH under the same DNI conditions

4. Conclusions

The application of solar collectors worldwide in industrial, residential and urban areas; It is extensive and is currently presented as systems in continuous development and research day by day. Within the classification of solar collectors, there is a group known as; "Solar concentration systems", where in turn, linear Fresnel reflector systems stand out with advantages in maintenance, expansion, cost investment, manufacturing, among others., Which enjoy great expansion in their designs and implementations, as ratified many study projects, technological development and research, found in the literature. This motivated the Research Group in energy, automation and control systems GISEAC, to manufacture an artisan prototype of this type of solar concentrator in the Technological Units of Santander, Colombia, for its application in alternative solar desalination systems.

To study the optical behavior of the artisan prototype of Linear Fresnel Reflector, an optical study is carried out applying the SolTrace and TONATIUH software. In conclusion, the most important results achieved in the study area: Optical efficiency increases proportionally with the number of reflective mirrors or reflection area, where the values showed efficiencies of 6.37% with SolTrace and 6% with TONATIUH for 10 Mirrors with direct solar radiation (DNI) 600 W / m ^ 2, while that the efficiency decreases to 5.08% with SolTrace and 4.57% with TONATIUH for 8 Mirrors with DNI 600 W / m ^ 2 and 3.82% with SolTrace and 3.66% with TONATIUH for 6 Mirrors with DNI 600 W / m ^ 2.

- The optical efficiency increases proportionally with the DNI value, where the values showed efficiencies of 6.37% with SolTrace and 6% with TONATIUH for 10 Mirrors with DNI 600 W / m ^ 2, while the efficiency decreases to 3.72% with SolTrace and 3.48% with TONATIUH for 10 Mirrors with DNI 350 W / m ^ 2. The tendency to decrease is maintained in the simulations that evaluate systems with 8 and 6 mirrors, varying the DNI.
- The concentration ratio (CR) increases with the number of reflective mirrors or reflection area, where the% variation of CR for analysis with DNI of 600 W⁄m ^ 2 decreases with respect to the evaluation with 10 mirrors by 17, 2% for 8 mirrors and 34.7% for 6 mirrors applying the SolTrace tool and 18.2% for 8 mirrors and 34.9% for 6 mirrors applying TONATIUH.
- Additionally, the concentration ratio (CR) increases with the increase in direct solar radiation (DNI), where the% variation of CR decreases with respect to the evaluation with 10 mirrors by 18.3% for analysis with DNI of 600 W ⁄m ^ 2 and 15.1% with DNI of 350 W⁄m ^ 2 for 8 mirrors and applying

the TONATIUH tool. This trend was maintained in the relationship of the results of the application of the two tools.

Additionally, this study compared the values obtained in the simulation process through SolTrace and TONATIUH, with the optical efficiency value determined through field experimentation with the full-scale system, highlighting:

- The SolTrace tool presents results with greater accuracy than the real efficiency value of the system, while TONATIUH tends to be less exact than SolTrace. The differential in the results obtained between the two tools is 5.1%. This shows that the tools used in the development of the study are reliable and allow the optical behavior of the LFC prototype to be accurately determined.

Finally, this study has made it possible to demonstrate the true optical behavior of the LFC prototype with precision for the given experimental conditions, where this type of solar thermal system stands out for its low maintenance and construction costs, mobility and operability, which encourages its use in various areas and regions worldwide to produce water or electricity, according to needs, under concentration of adaptability to the own resources of each place of implementation.

References

[1] Z. Said, M. Ghodbane, A. A. Hachicha, y B. Boumeddane, «Optical performance assessment of a small experimental prototype of linear Fresnel reflector», *Case Studies in Thermal Engineering*, vol. 16, p. 100541, dic. 2019, doi: 10.1016/j.csite.2019.100541.

[2] K. Lovegrove y W. S. Csiro, «1 - Introduction to concentrating solar power (CSP) technology», en *Concentrating Solar Power Technology*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2012, pp. 3-15. doi: 10.1533/9780857096173.1.3.

[3] P. Heller, «1 - Introduction to CSP systems and performance», en *The Performance of Concentrated Solar Power (CSP) Systems*, P. Heller, Ed. Woodhead Publishing, 2017, pp. 1-29. doi: 10.1016/B978-0-08-100447-0.00001-8.

[4] R. Pitz-Paal, «19 - Concentrating Solar Power», en *Future Energy (Third Edition)*, T. M. Letcher, Ed. Elsevier, 2020, pp. 413-430. doi: 10.1016/B978-0-08-102886-5.00019-0.

[5] K. Lovegrove y J. Pye, «2 - Fundamental principles of concentrating solar power (CSP) systems», en *Concentrating Solar Power Technology*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2012, pp. 16-67. doi: 10.1533/9780857096173.1.16.

[6] W. Van Sark y B. Corona, «Chapter 12 - Concentrating solar power», en *Technological Learning in the Transition to a Low-Carbon Energy System*, M. Junginger y A. Louwen, Eds. Academic Press, 2020, pp. 221-231. doi: 10.1016/B978-0-12-818762-3.00012-1.

[7] K. Lovegrove y W. Stein, «Chapter 1 - Introduction to concentrating solar power technology», en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 3-17. doi: 10.1016/B978-0-12-819970-1.00012-8.

[8] B. E. Tarazona-Romero, A. Campos-Celador, Y. A. Muñoz-Maldonado, J. G. Ascanio-Villabona, M. A. Duran-Sarmiento, y A. D. Rincón-Quintero, «Development of a Fresnel Artisanal System for the Production of Hot Water or Steam», en *Recent Advances in Electrical Engineering, Electronics and Energy*, Cham, 2021, pp. 196-209. doi: 10.1007/978-3-030-72212-8_15.

[9] H. D. Pedraza Corzo y D. M. V. Vesga Gomez, «DIMENSIONAMIENTO Y SIMULACIÓN DE UN SISTEMA SOLAR TÉRMICO TIPO FRESNEL PARA LA DESALINIZACIÓN DE AGUA DE MAR UBICADO EN EL DEPARTAMENTO DE LA GUAJIRA.», Pregrado, Universidad Autonoma de Bucaramanga, Bucaramanga, 2019.

[10] W. J. Platzer, D. Mills, y W. Gardner, «Chapter 6 - Linear Fresnel Collector (LFC) solar thermal technology», en *Concentrating Solar Power Technology (Second Edition)*, K. Lovegrove y W. Stein, Eds. Woodhead Publishing, 2021, pp. 165-217. doi: 10.1016/B978-0-12-819970-1.00006-2.

[11] G. Morin, J. Dersch, W. Platzer, M. Eck, y A. Häberle, «Comparison of Linear Fresnel and Parabolic Trough Collector power plants», *Solar Energy*, vol. 86, n.º 1, pp. 1-12, ene. 2012, doi: 10.1016/j.solener.2011.06.020.

[12] G. Cau y D. Cocco, «Comparison of Medium-size Concentrating Solar Power Plants based on Parabolic Trough and Linear Fresnel Collectors», *Energy Procedia*, vol. 45, pp. 101-110, ene. 2014, doi: 10.1016/j.egypro.2014.01.012.

[13] R. Abbas, M. J. Montes, A. Rovira, y J. M. Martínez-Val, «Parabolic trough collector or linear Fresnel collector? A comparison of optical features including thermal quality based on commercial solutions», *Solar Energy*, vol. 124, pp. 198-215, feb. 2016, doi: 10.1016/j.solener.2015.11.039.

[14] R. Abbas, M. Valdés, M. J. Montes, y J. M. Martínez-Val, «Design of an innovative linear Fresnel collector by means of optical performance optimization: A comparison with parabolic trough collectors for different latitudes», *Solar Energy*, vol. 153, pp. 459-470, sep. 2017, doi: 10.1016/j.solener.2017.05.047.

[15] B. E. Tarazona-Romero, Á. Campos-Celador, Y. A. Muñoz-Maldonado, C. L. Sandoval-Rodríguez, y J. G. Ascanio-Villabona, «Prototype of lineal solar collector Fresnel: Artisanal system for the production of hot water and/or water vapour», *Visión electrónica*, vol. 14, n.º 1, Art. n.º 1, ene. 2020, doi: 10.14483/22484728.16013.

[16] C. Tzivanidis, E. Bellos, D. Korres, K. A. Antonopoulos, y G. Mitsopoulos, «Thermal and optical efficiency investigation of a parabolic trough collector», *Case Studies in Thermal Engineering*, vol. 6, pp. 226-237, sep. 2015, doi: 10.1016/j.csite.2015.10.005.

[17] N. Kincaid, G. Mungas, N. Kramer, M. Wagner, y G. Zhu, «An optical performance comparison of three concentrating solar power collector designs in linear Fresnel, parabolic trough, and central receiver», *Applied Energy*, vol. 231, pp. 1109-1121, dic. 2018, doi: 10.1016/j.apenergy.2018.09.153.

[18] D. Mentado-Islas, S. Elizalde-Carrizo, D. Jiménez-Islas, y J. Azuara-Jiménez, «Simulación de un Concentrador Solar de Canal Parabólico mediante el Software SolTrace», *Revista de Prototipos Tecnologicos*, vol. 2, n.º 6, pp. 68-75, 2016.

[19] N. Kincaid, G. Mungas, N. Kramer, y G. Zhu, «Sensitivity analysis on optical performance of a novel linear Fresnel concentrating solar power collector», *Solar Energy*, vol. 180, pp. 383-390, mar. 2019, doi: 10.1016/j.solener.2019.01.054.

[20] M. A. Moghimi, K. J. Craig, y J. P. Meyer, «A novel computational approach to combine the optical and thermal modelling of Linear Fresnel Collectors using the finite volume method», *Solar Energy*, vol. 116, pp. 407-427, jun. 2015, doi: 10.1016/j.solener.2015.04.014.

[21] M. Hongn, S. F. Larsen, M. Gea, y M. Altamirano, «Least square based method for the estimation of the optical end loss of linear Fresnel concentrators», *Solar Energy*, vol. 111, pp. 264-276, ene. 2015, doi: 10.1016/j.solener.2014.10.042.

[22] E. Bellos y C. Tzivanidis, «Development of analytical expressions for the incident angle modifiers of a linear Fresnel reflector», *Solar Energy*, vol. 173, pp. 769-779, oct. 2018, doi: 10.1016/j.solener.2018.08.019.

[23] A. Heimsath, F. Cuevas, A. Hofer, P. Nitz, y W. J. Platzer, «Linear Fresnel Collector Receiver: Heat Loss and Temperatures», *Energy Procedia*, vol. 49, pp. 386-397, ene. 2014, doi: 10.1016/j.egypro.2014.03.042.

[24] Z. D. Cheng, Y. L. He, y F. Q. Cui, «A new modelling method and unified code with MCRT for concentrating solar collectors and its applications», *Applied Energy*, vol. 101, pp. 686-698, ene. 2013, doi: 10.1016/j.apenergy.2012.07.048.

[25] Y. Qiu, Y.-L. He, Z.-D. Cheng, y K. Wang, «Study on optical and thermal performance of a linear Fresnel solar reflector using molten salt as HTF with MCRT and FVM methods», *Applied Energy*, vol. 146, pp. 162-173, may 2015, doi: 10.1016/j.apenergy.2015.01.135.

[26] Y. Qiu, Y.-L. He, M. Wu, y Z.-J. Zheng, «A comprehensive model for optical and thermal characterization of a linear Fresnel solar reflector with a trapezoidal cavity receiver», *Renewable Energy*, vol. 97, pp. 129-144, nov. 2016, doi: 10.1016/j.renene.2016.05.065.

[27] Z.-D. Cheng, X.-R. Zhao, Y.-L. He, y Y. Qiu, «A novel optical optimization model for linear Fresnel reflector concentrators», *Renewable Energy*, vol. 129, pp. 486-499, dic. 2018, doi: 10.1016/j.renene.2018.06.019.

[28] D. Jafrancesco *et al.*, «Optical simulation of a central receiver system: Comparison of different software tools», *Renewable and Sustainable Energy Reviews*, vol. 94, pp. 792-803, oct. 2018, doi: 10.1016/j.rser.2018.06.028.

[29] NREL, «SolTrace | Concentrating Solar Power», *Concentrating Solar Power*, 2021. https://www.nrel.gov/csp/soltrace.html (accedido feb. 26, 2021).

[30] CENER, «Tonatiuh», *https://iat-cener.github.io/tonatiuh/*, 2021. https://iat-cener.github.io/tonatiuh/ (accedido feb. 26, 2021).
[31] P. L. Leary y J. D. Hankins, «User's guide for MIRVAL: a computer code for comparing designs of heliostat-receiver optics for central receiver solar power plants», Sandia National Lab. (SNL-CA), Livermore, CA (United States), SAND-77-8280, feb. 1979. doi: https://doi.org/10.2172/6371450.
[32] M. C. Stoddard, S. Faas, C. Chiang, G. Kolb, y D. Alpert, «Solergy (Beta Version 1)», Sandia National Laboratories, SOLERGY; 002377IBMPC00, mar. 2009. Accedido: mar. 03, 2021. [En línea]. Disponible en: https://www.osti.gov/biblio/1231189
[33] NREL, «System Advisor Model - SAM», *System Advisor Model - SAM*, 2021. https://sam.nrel.gov/ (accedido mar. 03, 2021).
[34] N. C. Cruz, J. L. Redondo, M. Berenguel, J. D. Álvarez, y P. M. Ortigosa, «Review of software for optical analyzing and optimizing heliostat fields», *Renewable and Sustainable Energy Reviews*, vol. 72, pp. 1001-1018, may 2017, doi: 10.1016/j.rser.2017.01.032.
[35] C. K. Ho, *Software and Codes for Analysis of Concentrating Solar Power Technologies*. 2008.
[36] S.-J. Bode y P. Gauché, «REVIEW OF OPTICAL SOFTWARE FOR USE IN CONCENTRATING SOLAR POWER SYSTEMS», p. 8, 2012.
[37] O. R. Delgado Carreño, «METODOLOGÍA PARA LA EVALUACIÓN DEL DESEMPEÑO ANUAL DE SISTEMAS DE CONCENTRACIÓN DE ENERGÍA SOLAR», Posgrado, Universidad Autonoma de nuevo leon, Mexico, 2019. [En línea]. Disponible en: http://bibing.us.es/proyectos/abreproy/5027/fichero/CAPITULO+3.pdf
[38] E. J. Duarte Celis, L. Sierra Roa, y J. A. Pulido Garzon, «Desarrollo de un sistema de captación de radiación solar difusa por medio de un sensor de superficie plana con el fin de analizar el comportamiento de la variable de radiación de la ubicación geográfica de las Unidades Tecnológicas de Santander.», Pregrado, Unidades Tecnologias de Santander, Bucaramanga, 2020. Accedido: abr. 05, 2021. [En línea]. Disponible en: http://repositorio.uts.edu.co:8080/xmlui/handle/123456789/5018