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# Analytic optical design of a Linear Fresnel solar collector with variable parameters

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## Abstract

This paper describes a design method to study the impact of Linear Fresnel Solar Collector (LFSC) geometry on its efficiency. The proposed approach is based on an optical modeling using a combination of both ray tracing and Monte Carlo method to evaluate the influence of the geometric parameter variation on the solar energy collected on the receiver, and to simulate the influence of loss mechanisms. Therefore, for a unit of LFSC with 50 m length and a receiver width of 1 m, the optimum gap should be 10 cm in order to minimize blocking and shadowing effects, the number of mirrors stripes should be in the range of 9 rows on each side. In addition, given the solar flux distribution on the receiver surface, its width could be reduced from 1m to 0.6 m consequently the receiver surface is also reduced to 30 m². Hence, the optimized prototype has a concentration ratio of 37.5 %, an intercept factor of 0.795 and its optical efficiency is about 0.74. Once all geometric parameters are selected, it was necessary to study the optical behavior of the primary mirror field under typical Tunisian meteorological conditions. A database of meteorological station installed in southern Tunisia is used to calculate thermal flow transferred to the working fluid from the sunrise to sunset. The optical efficiency varies from 0.4 in winter to reach 0.7 in summer, thermal flow generated increases from 350kW to 718.27kW.

## 1. Introduction

The energy demand is growing in strength over the world, as well as the economic growth and the environmental pollution [1]. Concentrated solar power technologies can generates about 7% of the worldwide electricity demand by 2030 and it may reach 25% by 2050 [2]. The linear Fresnel solar collector is an attractive alternative. It is an advantageous technology. In addition, it is useful for both thermal and electrical applications. The design of linear Fresnel solar collectors (LFSC) follows the principle of the Fresnel lens, which is developed by the French physist « Augustin-Jean Fresnel » who developed a multi-part lens for use in light houses in the 19$^{th}$ century [3]. The idea behind this invention was to reduce the quantity of material used in the conventional lens. This was done by dividing the lens into concentric section in order to focus light horizontally and make it visible over longer distances [4. The first LFSC theory was developed by Baum et all in 1957 [5]. Four years later, in 1961, Francia was the first to apply this method to a large scale system [6]. The first oil crisis in 1973 triggered the generation of electricity using solar. In the 80's, the interest in linear Fresnel technology grew in strength, large numbers of numerical and experimental studies have been performed: Choudhury and Seghal [7] have studied the effect of the receiver height variation on the tilt of each mirror. Also, they simulated the variation of the mirrors rows number on the power concentrated onto receiver. The linear Fresnel prototype was made of reflecting mirrors commercially available "a back-coated mirrors with a reflectivity equal to 0.6". Their study showed that; with the low reflectivity mirror stripes, linear Fresnel solar collector is able to produce a temperature higher then 350°C, its average concentration ratio is 18. The study of Negi et all. [8] was focused on the receiver tube absorptivity. They made a comparative study between three types of coated absorbers tubes (ordinary black paint, Cobalt oxide and MAXORB foil). Results showed that the improvement of the absorptivity leads to increase the fluid temperature. An LFSC with optical design and concentration characteristics was studied by R.P. Goswami et all [9]. A ray tracing method was used for the design of two different approaches of a linear Fresnel solar collector. Results show that triangular receiver configuration is more efficient compared to the flat vertical receiver. The distribution of reflected rays is uniform in both sides of the absorber surfaces. Regarding the primary mirror field, the equal width mirror stripes configuration is more advantageous, it reflects the incident rays onto the receiver with a uniform way. Many Fresnel power plants are currently suppliers for heat generation and electricity sector [10]. In 2000, Mills and Morrison developed the compact linear Fresnel solar reflector concept, using several stationary absorbers spared between the mirror rows. Based on Mills and Morrison [11] technology ARIVA SOLAR (formerly known AUSRA) commercialized the compact linear Fresnel solar collector, with an absorber made only of several tubes without secondary mirror and with primary mirror field using flat mirrors.

In 2009, NOVATEC SOLAR (formerly known NOVATEC BIOSOL) commissioned the Puerto Errado LFSC demonstration power plant of 1.4MW near Calasparra in the southern of Spain. This was followed by the erection of 30 MW Puerto Errado 2 LFSC power plant on the same site in 2013. Further plants with different size have been erected worldwide, however with slower pace than other concentrated solar power technologies, i.e. parabolic trough and solar tower systems [12].

Compared to other technologies, LFSC have economic advantages; it seems to have an important potential to reduce the Levelized Cost of Energy. Nevertheless, the number of the LFSC plants in operation is very low compared to parabolic trough [13]. Linear Fresnel technology is considered as a prospective method to heating process (in the range of 10 kW to 10 MW), due to its simplicity in structural design and its low manufacturing costs [10].

P. L. Singh et all developed a simulation of a linear Fresnel solar collector prototype with a variable number of mirror stripes. The overall efficiency of the optimized design has been studied [14]. They evaluated a LFSC with 10, 15 and 20 mirrors. The researchers found that increasing the number of mirrors affects directly the time needed to reach the stagnant temperature. Nevertheless, the overall collector efficiency decrease with the increase of reflective surface. The study shows that the optimum mirror number should be in the range of 10-15 with an optimum mirror width between 10 and 12 cm.

Another study given by SKY FUEL (the Sunrise of Solar Power) includes the development of a Linear Fresnel solar collector considered for direct molten salt that is compared with a parabolic trough using ASAP ray-tracing software [15].

Jie He et all have developed an optical design of a LFSC [16]. A new design method was used to evaluate the mirror efficiency, through the study of the influence of geometric parameter variation on optical efficiency.

A new approach of two-axis LFSC was experimented and evaluated by D. Chemisana et all [17]. They have demonstrated that there is many manufacturing factor play an important role on the optical quality such as: metallic structure stresses, twisting, bending and sagging.

LFSC is suitable for different scales: in large scale, it is useful for electricity generation and industrial heat process. In addition, it suppliers for process heat application [18], solar cooling and polygeneration. Compared to other technologies, LFSC is the best suited technology for rooftop installation and building integration, due to this advantage, it can easily meet industry requirements.

This paper describes a design method to study the impact of linear Fresnel solar collector geometry on its efficiency. This method is based on an optical modeling using a combination of both ray tracing and Monte Carlo technique to evaluate the influence of the geometric parameter variation on the solar energy collected on the receiver, and to simulate the influence of loss mechanisms (shading, blocking, cosine effect, end losses, etc). This study aims to give an analytical optical design in order to reduce optical losses due to the daily sun motion.

In the first section, we will describe the LFSC technology, its advantages and its drawbacks.

The second section presents the design strategy; a detailed description of the LFSC optimization technique is described. The software TONATIUH is used to generate a random solar radiation and to calculate the quantity of rays reflected by the primary mirror field and focused onto the receiver. All prototype parameters, considered as variables, such as the gap between two adjacent mirrors, the number of rows and receiver height are performed. The simulation method and the used assumptions were detailed.

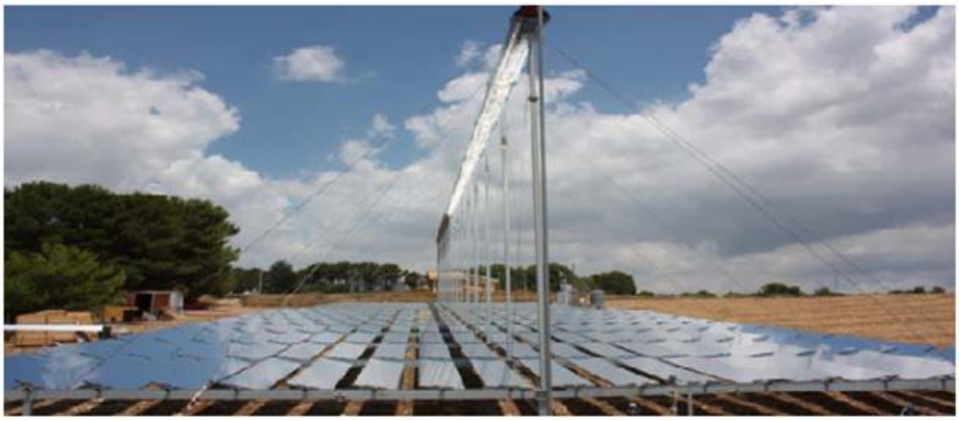
The simulation results holding an optimized design are discussed in the last section, the influence of all geometrical parameters is carried out. During this design process, LFSC presents an important degree of freedom, all geometrical collector parameters are selected carefully in order to minimize optical losses and consequently to improve the collector efficiency. Once all geometric parameters are selected, it was necessary to study the optical behavior of the primary mirror field under typical Tunisian meteorological conditions. In this section, a database of meteorological station installed in southern Tunisia is used to calculate thermal flow transferred to the working fluid from the sunrise to sunset, and consequently to study the operation conditions in addition to the collector response in different seasons.

## 2. Materials and methods

### *2.1. Linear Fresnel technology*

The main components of the linear Fresnel solar collector system [4] are shown in Fig.1:

- Primary mirrors filed (1): made of flat parallel mirror stripes. The most important design parameters are: the stripes width, the number of rows and the gaps between two consecutive mirrors. Compared with parabolic trough, LFSC has more optical losses. Fresnel collectors do not only have longitudinal losses; they are also affected by transversal cosine losses because each mirror tracks the sun individually. At high transversal incidence angles, the parallel mirror stripes shade/block each other.
- Receiver (2): the main components of the receiver are: the absorber tube and the secondary mirror. Primary mirror field alone cannot alone accumulate the required power. The idea is to increase the efficiency without generating more thermal losses. It is necessary to add a secondary mirror above the absorber tube to mitigate this optical inaccuracy and to improve the intercept factor. In addition, it increases the width of the target surface without affecting the absorber tube. The secondary mirror configuration should be adapted to concentrate incoming radiation into the absorber tube.
- Tracking system: LFSC have only single-axis tracking. The motion of parallel mirror stripes depends only on the sun path and not on the mirror position. Each mirror tracks the sun individually, at the same angular velocity



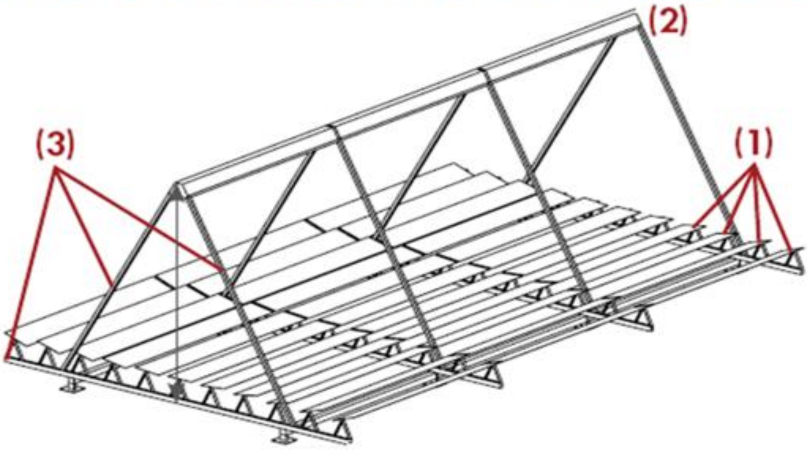



**Figure1:** (A.1) Linear Fresnel prototype installed in Sicily, (B.1) Linear Fresnel solar collector component

The development of the parabolic trough power plant is highly advanced. However, linear Fresnel solar technology admits several advantages. The concept of this technology is simple, it allows the use of flat plane mirror which is easier to manufacture. Curved mirrors are also used to get higher concentration, this kind of mirror is deformed elastically by a simple mechanical systems. The LFSC technology admits a low susceptibly to the wind effects. This slightest wind resistance allows a lighter structure. Consequently, the tracking systems are simple small engines. Flexible connections are not needed in such kind of collector; a simple stationary

receiver system is used. The assembly of the entire solar field is not complicate, a great part are composed of elements of simple technologies.
Compared to solar tower and parabolic trough power plants, the LFSC admits the higher land use efficiency. It can be built on site with simples local capacities. Consequently, the LFSC construction cost is low. The maintenance is easy; the cleaning of the mirrors may even be automated: Novatec solar technology used patented cleaning robots with very low water use. The CSP power plant are dedicated to generate electricity, only LFSC technology can generate directly steam, in this case water is used as a heat transfer fluid. Ultimately, LFSC technology is easily transformable to different scales: it can be applied in the range of 10 kW to hundreds of MW [6].

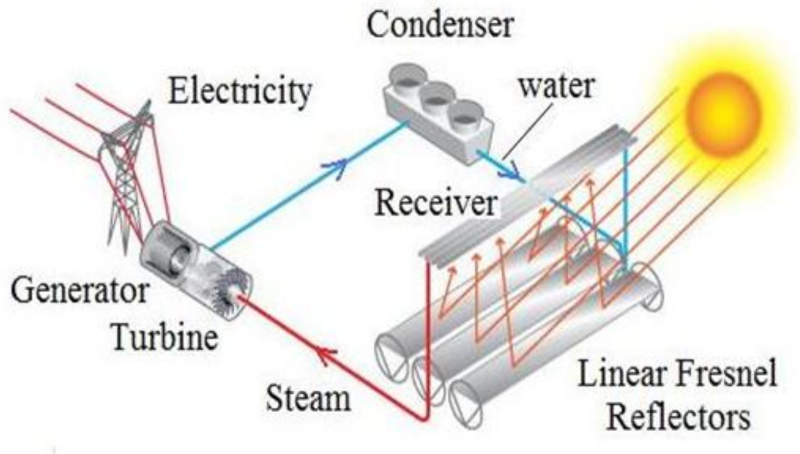



**Figure 2:** A typical Fresnel solar power plant

The LFSC is a young technology compared to parabolic trough; it has a slightly less optical efficiency. During its operation, the linear Fresnel reflector system tends to work less time: it starts later in the morning and it stop at early afternoon. Excepting at noonday, it generates a higher amount of power (comparison for equal reflective surface). In addition, LFSC are affected by both longitudinal and transversal losses. At high transversal incident angle, a percentage of reflected rays are lost due to the shadowing and the blocking (Figure 3).

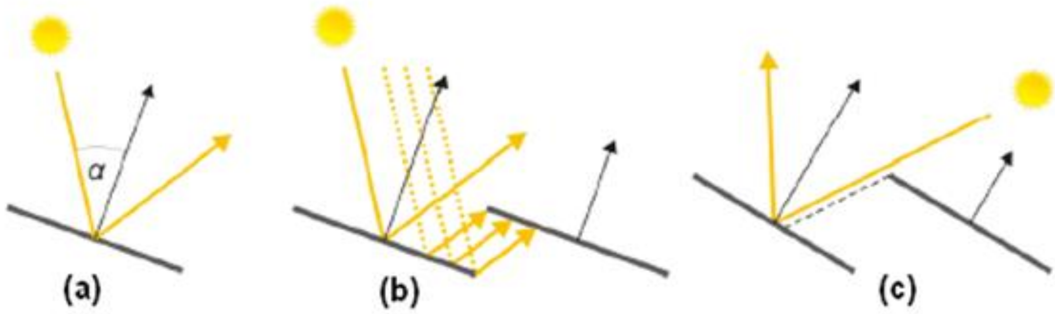



**Figure 3:** Scheme of the optical losses: (a) cosine losses, (b) blocking, (c) shadowing [18]

In concentrating solar technology, the optical quality is a key parameter, it influence directly the overall solar power plant efficiency. Optical losses are generally due to the inaccuracy of mirrors which concentrate the incidents rays. However, based on an optical study, a linear Fresnel solar collector scale is selected which had the minimum optical losses.

*2.2. Design strategy of linear Fresnel solar collector:*

– *Geometrical parameter of linear Fresnel solar collector:*

In linear Fresnel technology, the incident radiation is reflected and focused by the primary mirror field onto a linear absorber. Each mirror tracks the sun individually; the motion of mirror stripes should be performed with high precision to minimize the optical losses**.**

To focus the incident solar radiation into a single focal line, the unique shape recommended is the parabolic shape. Nevertheless, manufacturing a high number of small parabolic mirrors with specific curvature radius is difficult and costly [19].

Therefore, the use of the curvature mirror shape can be an alternative solution [20]. In such case, each mirror in the field is defined by four specific parameters: the position on the primary mirror field, its focal length, the tracking angle and the radius of curvature. All of those parameters are detailed:

- The mirror position: In the studied case, primary mirror field is consists of the same number of rows arranged symmetrically on both sides (Fig. 4), (xi) define the position of the ith mirror : $x_i = \frac{1}{2}(W+G)+(i-1)(W+G)$

Where G is the gap between two successive rows, and W is the mirror width. During this study, the gap between mirror stripes in series is not taken in consideration.

- The focal length: According to the mirror position, the focal distance can be defined as: $f_i = \sqrt{(x_i^2 + h^2)}$

As shown in the figure below, h is the receiver height.

- The tracking angle: in order to obey to the Snell-Descartes low (the incident angle is equal to the angle of reflection), each mirror admits its own normal surface. The tracking angle ψi is then defined by Rabl [21] as the tilt angle: angle between the horizontal plane and the plane containing the reflective mirror: $\psi_i = \frac{\phi_i - \theta}{2}$

Where ϕi is the angle between the optical axis and the line joining the mirror and the receiver, and θ is the incident angle.

At noon, the incident angle is close to zero, and then the tracking angle is: $\psi_i = \frac{\phi_i}{2}$

- The radius of mirror curvature: this parameter depends on both tracking angle and focal length $r_i = \frac{2f}{\cos\psi}$

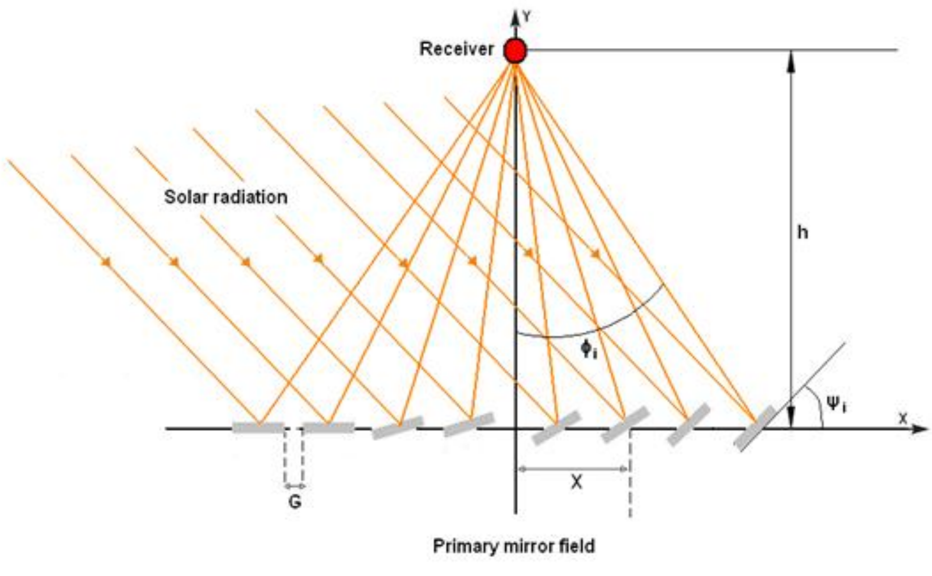



**Figure 4:** Characteristic of simulated collector

– *Simulation of linear Fresnel solar collector:*

The optical analysis is made using the "TONATIUH" software. "TONATIUH" is an open source program for the opto energetic simulation of solar concentrating system".

It is a Monte Carlo ray tracer dedicated to the optical simulation, TONATIUH analyze the incidents and the reflected rays in order to quantify the flow rate on the receiver [22][23]. The input data needed for the simulations are: the collector geometric parameters, the location coordinates which are useful to calculate the sun position, the number of generating rays and the Random generation method. In addition, an ECMA [24] script code was developed to calculate some additional parameters such as: the mirror position, the focal length

and the time variation. Under these specific conditions, the mirrors are accurately oriented using a tracking system already defined when designing the collector. TONATIUH software is able to locate each reflected ray and generates x, y and z coordinates of all rays. Rays coordinates are then needed to determine the number of rays intercepted on the receiver; consequently the intercept factor is estimated.
Linear Fresnel solar collector consists of a variable number of mirrors, each mirror has1.25m width and 50m length. Furthermore, all mirrors are slightly curved to better focus incident rays on the receiver; each mirror admits its own focal length. The tracking system drives the mirror stripes to focus incident sunlight onto a linear receiver located above the primary mirror field. All mirror stripes track the sun at the same velocity, the tracking motion is supposed to be perfect and the incident radiation is perpendicular to the mirror surface.

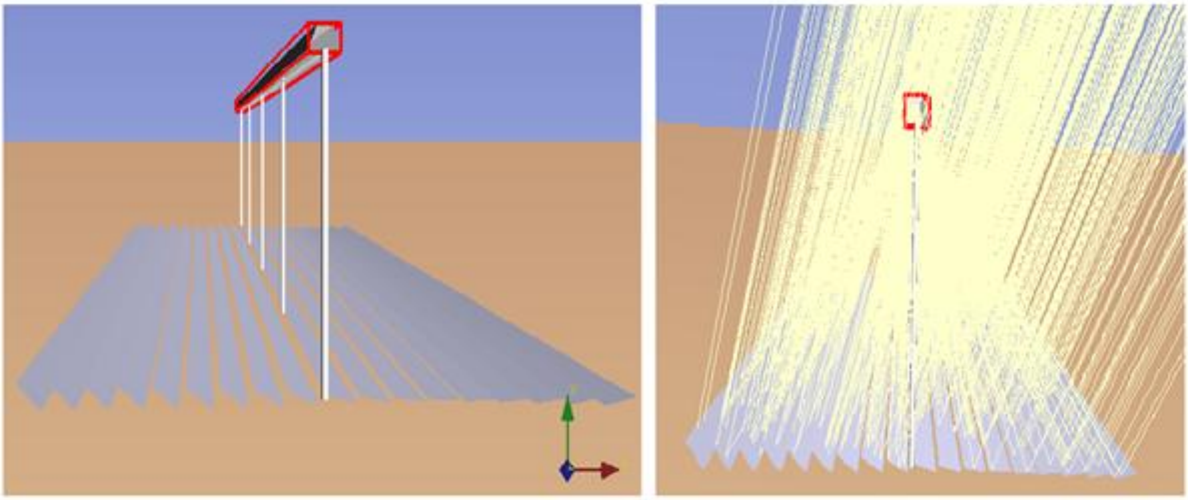


**Figure 5:** 3D module of linear Fresnel prototype built using TONATIUH software

The studied linear Fresnel prototype design is simulated under Tunisian climatic conditions at Borj Cedria near Tunis, the latitude is about 36°44' and the longitude is 10°21', only heat used as an output. For making an efficient design of such type of collector, it is necessary to analyze the optical performance. The 3D module of linear Fresnel prototype is built using TONATIUH software.
During this study, some simplifying assumptions were made:

a. The incident sun rays are parallel
b. The sun is a flat surface
c. The absorber is a flat rectangle
d. The mirrors field is north/south oriented
e. The field height above the ground is 0.75 m

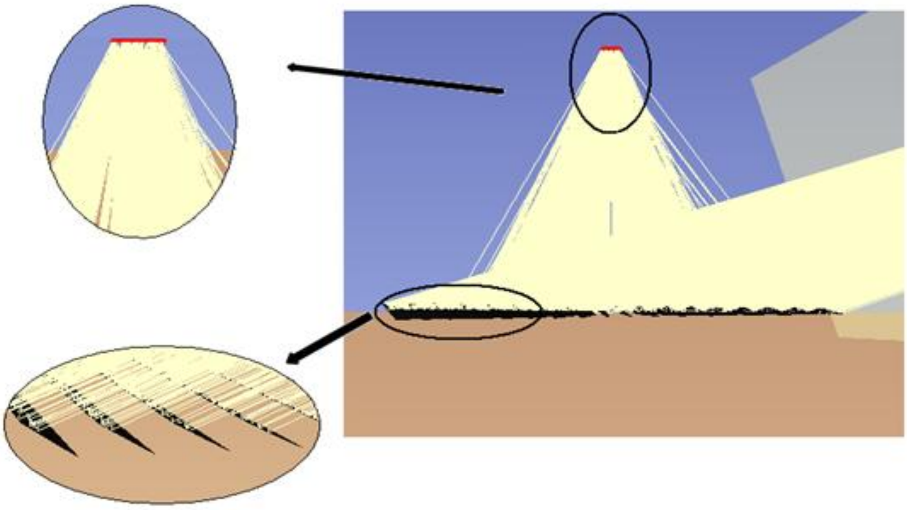


**Figure 6:** Path of rays on linear Fresnel solar collector using ray tracing method

– *Determination of the optical efficiency and the power collector on the receiver*

In both sides of primary mirror field, the mirror stripes are symmetrically arranged. The optical efficiency of linear Fresnel solar collector is calculated with the following relations:

$$\eta = \alpha * \rho * \tau * IC$$

With:

- τ: transmittance of the receiver glass
- α: absorbance of the receiver
- ρ: the mirror reflectance
- IC is the intercept factor; which is defined as the ratio of the flux reaching the receiver over the incident beam irradiance [25]. The intercept factor gives a clear idea about optical losses: the blocking, shading, the optical imaging, tracking errors and the assembly tolerances.

The power of Fresnel collector was computed using:

$$Power = N * P$$

Where N is the number of photons which reach the receiver and P is the power per photon.

## 3. Results and discussion

*3.1. Test of real case*

TONATIUH software generates a random incidence sun light (random generator is Mersenne Twister). The first step is; testing the influence of random generation on the optical efficiency. Results presented in table 1 show that the relative error is close to zero, and that the random error does not affect the optical efficiency.

**Table 1:** The influence of the random generation on the optical efficiency

| Azimuth | Zenith | Number of rays generated | Optical efficiency (%) | Number of generated rays | Optical efficiency (%) | relative error |
|---|---|---|---|---|---|---|
| 156.766 | 61.5939 | $5*10^5$ | 0.468166 | $10^5$ | 0.46809 | 0.020 |
| 123.933 | 22.4242 | $5*10^5$ | 0.451512 | $10^5$ | 0.45141 | 0.022 |
| 243.262 | 25.6898 | $5*10^5$ | 0.55783 | $10^5$ | 0.55669 | 0.204 |
| 269.257 | 48.8228 | $5*10^5$ | 0.60312 | $10^5$ | 0.60354 | 0.069 |

In order to validate the software Tonatiuh, it is necessary to study a real case. The linear Fresnel commercialized collector Novatec is simulated in this regard with collector's parameters shown in the fig. 7.

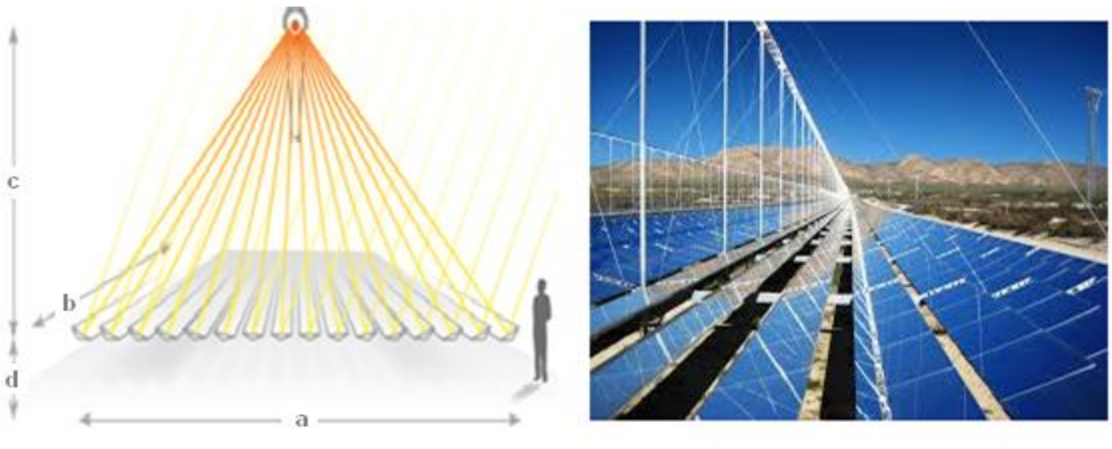



**Figure 7:** Fresnel collectors of Novatec installation

Using Novatec parameters, two optical simulation runs are made. The first run uses flat plat mirrors and the second uses curved mirrors. Results show that the optical efficiency of the simulated Novatec collector using flat plat mirror is equal to 0.3 %. But, in the second case, it is more important it can reach 0.69 %. The optical efficiency given by Novatec brochure is 0.67 %, it is clear that Novatec uses curved mirror to secure its optical efficiency value, the flat mirror admits widest image on the receiver and consequently lowest intercept factor.

According to these results, it is concluded that Tonatiuh software is suitable for this research for delivering reliable results.

**Table 2:** Novatec parameters

| Technical Data of Control Unit | |
|---|---|
| Width (a) | 16.56 m |
| Length (b) | 44.8 m |
| Absorber tube height above primary reflector level (c) | 7.4 m |
| Height of primary reflector level (d) | 0.75-1.05 m above ground level |
| Recommended minimum clearance between parallel rows | 4.5 m |
| Aperture surface of primary reflectors | 513.6 m² |
| Minimum row length | 5 control units, 224m in length |
| Maximum row length | 22 control units, 985.6m in length |

*3.2 Optimization of the gap between two adjacent mirrors stripes*

The first step is the optimization of the gap between two adjacent mirror rows. In order to optimize the gap between two stripes, a variation of the sun inclination is necessary to study the response of the row in case of high incident angle. Simulated linear Fresnel model consists of 32 rows (16 in each side), the receiver height varies from 8 to 19 m and the gap varies from 0 to 0.7 m.

Simulation results show that, the highest value of intercept factor can be achieved when the gap between the mirror stripes is null. In such a condition, linear Fresnel prototype functions similar to parabolic trough collectors. This case will be neglected since it causes many difficulties in manufacturing and maintaining of mirrors stripes and in the installation of the cleaning and tracking systems.

According to Fig.8, the curve corresponding to gap values from 0.2 to 0.7 m have the same optical, in which they are all superposed. In the case of a gap value equal to 0.1 m, the intercept factor is more significant, it increases from 0.5% to 0.7%. Therefore, the optimal gap (0.1 m) chosen will be constant for the rest of this study.

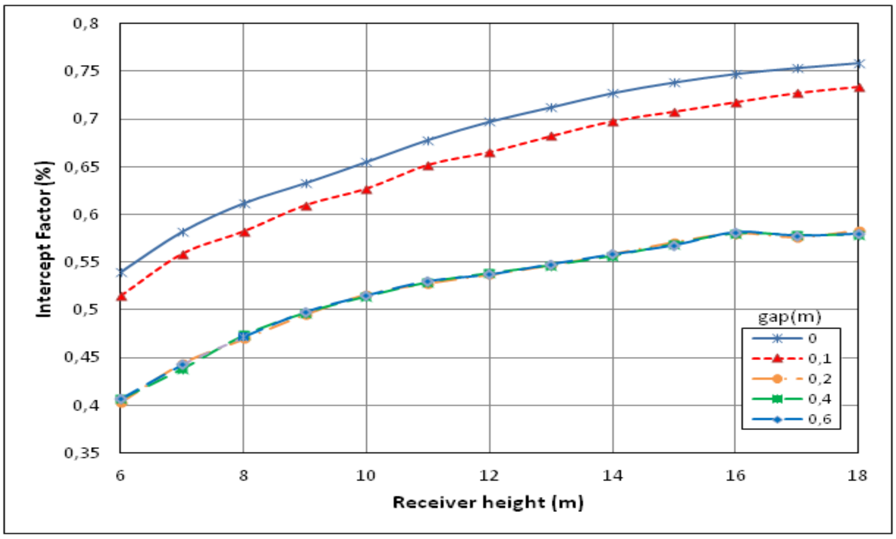



**Figure 8:** Intercept Factor according to the receiver height at 10 h (local time).

The second step is the study of the influence of the receiver height along a day. An LFSC is a single axis tracking collector. In such a case, the cosine loss depends on the collector orientation, site and time. The simulation during all the day (from 8 h to 19 h) show that the intercept factor admits two picks; the first one is on the morning and the second one is at 15 h.

As shown in the Fig.9, the intercept factor reaches its maximum when the incident angle is high and it decreases at noon when the incident angle is close to zero, which is due to the orientation of the LFSC (North/South).

If the Linear Fresnel solar collector is orientated in the North/South direction, it tracks the sun from East to West. It reaches the maximum value of the intercept factor two times, the first in the morning and the second in the afternoon which correspond to the lowest cosine losses. But, it has the lowest intercept factor value at noon, consequently the highest cosine loss [26]. Compared to the East/ West configuration, the North/South configuration has more constant annual output; in summer, it collects a big amount of energy more than the other configuration. Although, it has a problem in winter, it collects less energy than the East/ West configuration [27].

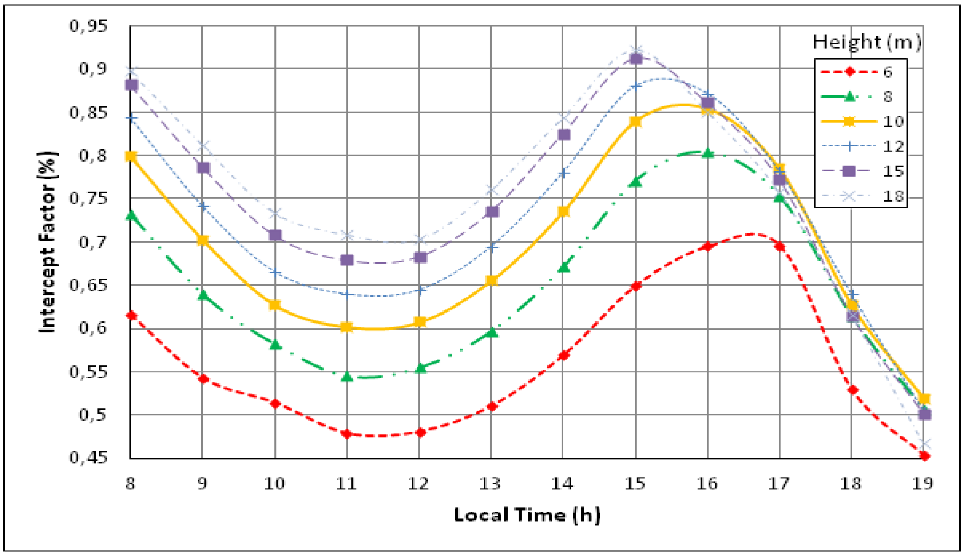



**Figure 9:** Intercept Factor according to time under different receiver height.

*3.3 Optimization of receiver height and number of rows*

The second step of the experiment is to optimize two parameters: the receiver height above the primary mirror field and the number of rows. The time is fixed during this experiment to be 13 h with an incidence angle close to zero, in order to minimize the blocking and shadowing effects.

The results indicated that the optical efficiency of the LFSC decreases with an increasing number of mirrors rows. Therefore, the quantity of block and shadow generated by rows far from the receiver has a bigger effect than the quantity of reflected solar irradiation near the middle of the primary field.

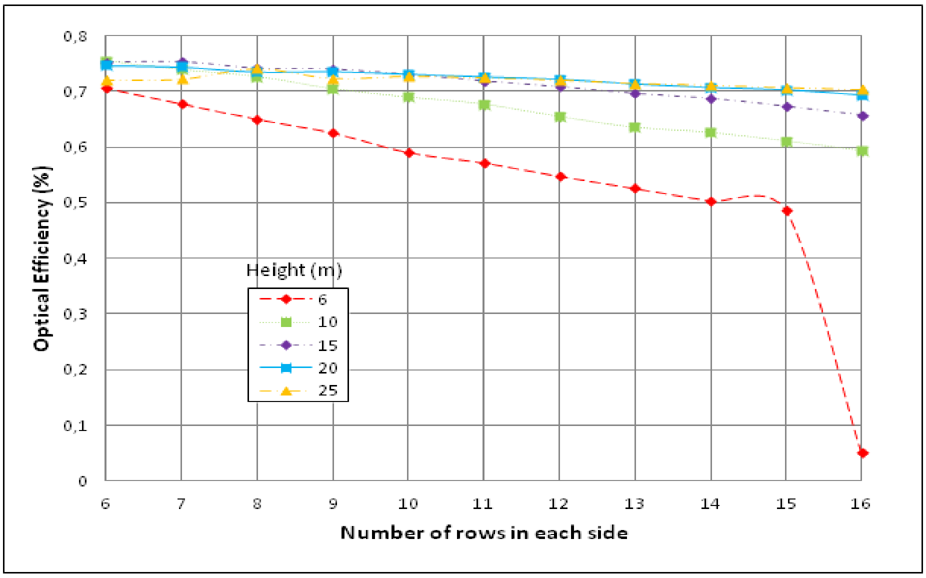



**Figure 10:** Optical efficiency according to the number of rows in each side

Regarding the receiver height from the mirrors field, it is noticed that the optical efficiency is directly proportional to the receiver height. Fig. 10 shows that the higher the receiver is the lower should be the blocking and shadowing effect. The spillage effect is defined as solar beams that miss hitting the receiver due to design specifications or errors. This effect increases for an LFSC that consists of a large reflective area and low receiver height. Before choosing the optimal receiver height, two parameters must be taken into consideration: the blocking and shadowing effect and the spillage losses [28]. New characteristics design should be selected to have minimum block and shadow between rows, and the minimum spillage losses

Figure11 shows that the amount of solar power collected on the receiver increases with an increase in receiver height and number of rows. The figure demonstrates a significant increase in absorbed solar power on the receiver by increasing the receiver height up to 15 m. above this value, no further effect on power absorbed on the receiver can be observed when increasing its height in steps of 1 m.

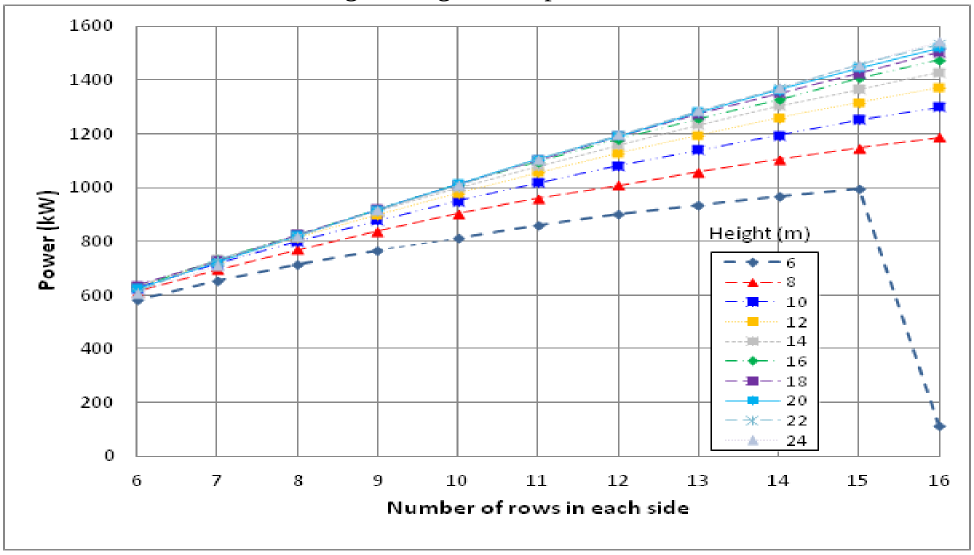



**Figure 11:** The variation of the power according to the number of rows (at different receiver height).

Generally, further increasing the receiver height would affect those LFSC, which have a reduced number of reflective surfaces. According to Fig.11, collectors consisting of 12 rows (6 in each side), with a total reflective surface of 750 m² would generate 600 W under specified conditions regardless of the receiver height.

*3.4 Study of the receiver dimension:*

To optimize receiver dimension, the same software is used. Knowing that in this study the receiver is assumed to be a flat rectangular plate, the photon distribution on a flat surface is defined during this experiment. All mirrors are curved in this study to better focus reflected beam onto the receiver. In order to collect the maximum amount of photons, each mirrors row is designed with its own focal length and its tracking system.

The photon distribution is shown in Fig.12 in a Gaussian distribution: a high number of photons are accumulated on the center of the flat rectangle and this number decreases when moving far from the center. In this case the receiver width can be reduced from 1 m to 0.6 m.

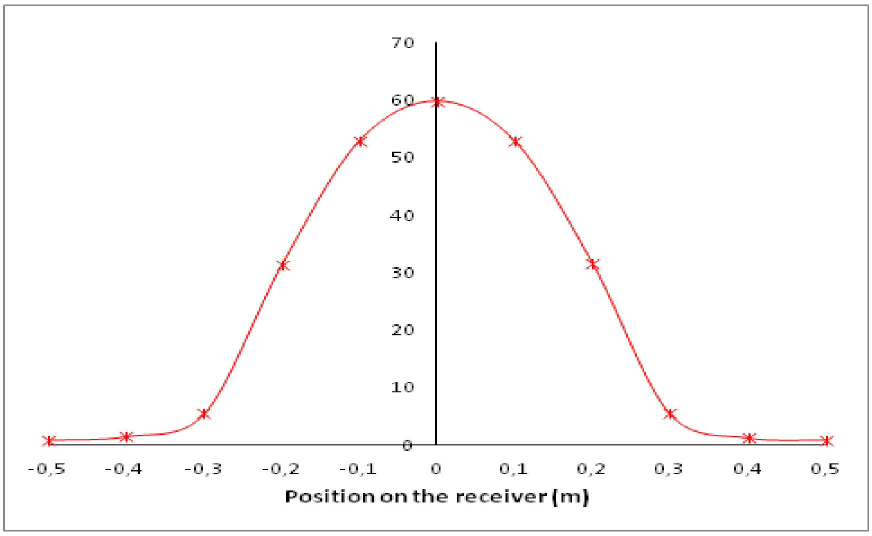



**Figure 12:** Photon distribution on the receiver (%)

*3.5 Configuration of the primary mirror field*

To calculate the radius of mirror curvature, the incident angle is considered equal to zero, the table 4 presents all mirror parameters defined on the section 3.1. The mirrors position (i) is counted from the center of the field to its extremities.

**Table 3:** Mirrors parameters

| Mirror position | x(m) | f(m) | ϕ (°) | ψ (°) | r (m) |
|---|---|---|---|---|---|
| 1 | 0,675 | 15,015 | 2,576 | 1,288 | 30,037 |
| 2 | 2,025 | 15,136 | 7,688 | 3,844 | 30,340 |
| 3 | 3,375 | 15,375 | 12,680 | 6,340 | 30,939 |
| 4 | 4,725 | 15,726 | 17,484 | 8,742 | 31,822 |
| 5 | 6,075 | 16,183 | 22,048 | 11,024 | 32,975 |
| 6 | 7,425 | 16,737 | 26,336 | 13,168 | 34,378 |
| 7 | 8,775 | 17,378 | 30,328 | 15,164 | 36,010 |
| 8 | 10,125 | 18,097 | 34,020 | 17,010 | 37,850 |
| 9 | 11,475 | 18,885 | 37,417 | 18,708 | 39,878 |

*3.6 Comparison between the studied design and existing LFSC*

The table 4 shows a comparison between the performed linear Fresnel prototype and same commercial collectors.

**Table 4:** Comparison between existing linear Fresnel solar collectors and the studied case

| Company | Primary mirror field size [m²] | Number of mirror stripes | Mirror width [m] | Total surface [m²] | Ground Cover (%) | Receiver height [m] | Power range |
|---|---|---|---|---|---|---|---|
| **Solar power group** | 21x100 | 25 | 0.6 | 1433 | 68 | 8 | 1 MWel |
| **CNIM** | 19x52 | 14 | 1 | 720 | 73 | 8 | 0.5 Wth |
| **Helio Dynamics (HD10)** | 4x6 | 4 | 0.1 | 14 | 60 | 2.7 | 8 kW |
| **RAPSODEE** | 3x1,5 | 21 | 0.1 | 3,15 | 70 | 1.8 | 3 kW |
| **New design** | 24,2x50 | 18 | 1.25 | 1210 | 93 | 15 | 0.916 MW |

The collector installed by Solar power group admit a total reflective surface (1433 m²) higher than the reflective surface of the studied case, the difference between the two areas is more than 200 m². In spite of that, both collectors generate a power in the range of 1MW. The benefit of our design over the Solar power group prototype is the use of less number of mirrors, consequently, the number of tracking engines is reduced.

In addition, the optimized prototype admits the higher land use efficiency 93 % compared to 68 %. The land use efficiency is defined as the ratio of the covered area by the mirror strips on the overall land used.

*3.7 Simulation of the optimized linear Fresnel design in different regions in Tunisia*

In the following section, the influence of the geographic parameters on the studied prototype is analyzed. The idea is to study the effect of latitude and longitude on the solar power plant efficiency. The new collector design is simulated and studied in different regions in Tunisia whose geographic coordinates are detailed in table 5.

Tunisia is relatively small country located on the northern Africa; its area is about 163.610 Km². Tunisia is between longitudes 7° and 12°E and latitudes 30° and 38°N. Consequently, the variation of both latitude and longitude is not very high.

**Table 5:** Site localization

| Country | Latitude | Longitude | Azimuth (°) | Zenith (°) |
|---|---|---|---|---|
| **Borj el Khadra** | 30.2517 | 9.5548 | 140.961 | 8.607 |
| **Gabes** | 33.8833 | 10.1166 | 154.534 | 11.444 |
| **Douz** | 33.4614 | 9.0294 | 149.018 | 11.5 |
| **Tozeur** | 33.9166 | 8.1333 | 146.67 | 8.133 |
| **Nafta** | 33.8761 | 7.8803 | 145.63 | 12.3659 |
| **Sfax** | 34.7333 | 10.7666 | 158.862 | 12.011 |
| **Sidi Bouzid** | 35.0333 | 9.5 | 154.35 | 12.698 |
| **Tajerouine** | 35.8833 | 8.55 | 152.479 | 13.8045 |
| **Sousse** | 35.8256 | 10.6083 | 159.983 | 13.0812 |
| **El Kef** | 36.1822 | 8.7147 | 153.606 | 14.0137 |
| **Borj Cedria** | 36.4421 | 10.2141 | 159.379 | 13.7691 |
| **Bizerte** | 37.2666 | 9.8666 | 159.309 | 14.6395 |
| **Tabarka** | 36.9544 | 8.758 | 155.037 | 14.6972 |
| **Ras Angela** | 37.3397 | 9.7483 | 158.973 | 14.7437 |

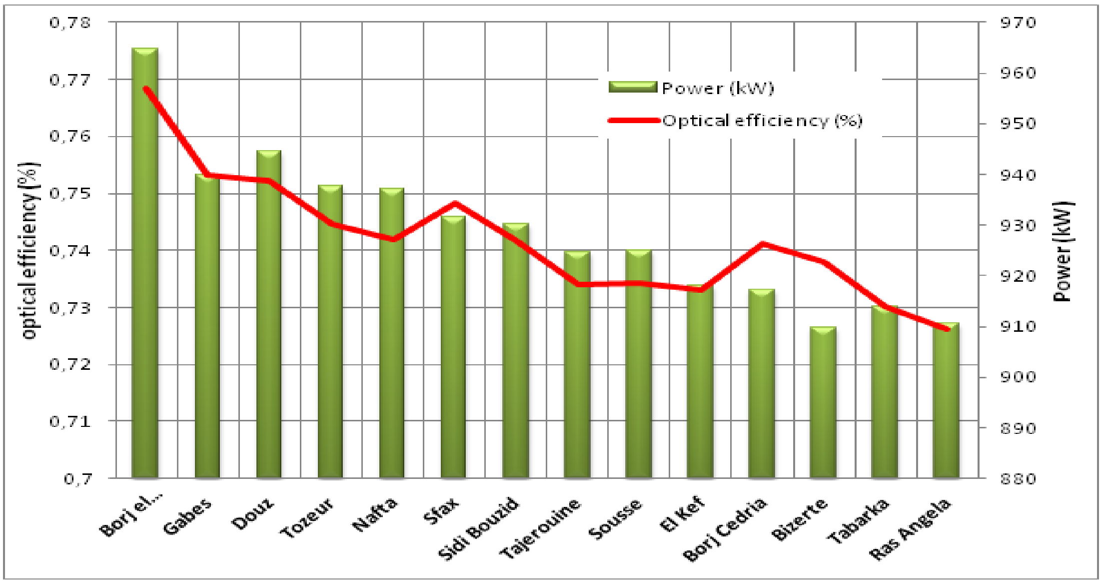



**Figure13:** Power and optical efficiency in the selected regions

This variation cannot be taken in consideration on our case. However, in the case of a large scale solar power plant, it may have influence.

*3.8 Daily simulation results*

During this study, only optical analysis is carried out. However, it is essential to calculate thermal flow transferred to the working fluid, located on the receiver component, to study the profitability of the optimized prototype and to validate it.

Thermal flow is reduced by collector efficiency, it is defined as:

$$\phi_{thermal} = S_m * DNI * \eta$$

With $S_m$ is the reflective surface.

$$S_m = W * L * n$$

To study the primary mirror field optical behavior, the LFSC operation from the sunrise to sunset is performed. The performance of the optimized LFSC design for single days is studied; four days are chosen to describe the operation condition and the LFSC response in each season (January, April, July and October).

In general case, the LFSC is less efficient during the early morning and the late afternoon hours, due to the high incident angle. The figure below shows the operation conditions during winter, the date was chosen arbitrary the 7$^{th}$ January. The LFSC is switched on at 9am and switched off at 17pm, the operation time is limited to 9 hours. Thermal flow transferred to the working fluid varies from 258.08 to 465.55kW, it reach its maximum values at noon. During winter, the sun's declination is low; which generates more optical losses and consequently low optical efficiency.

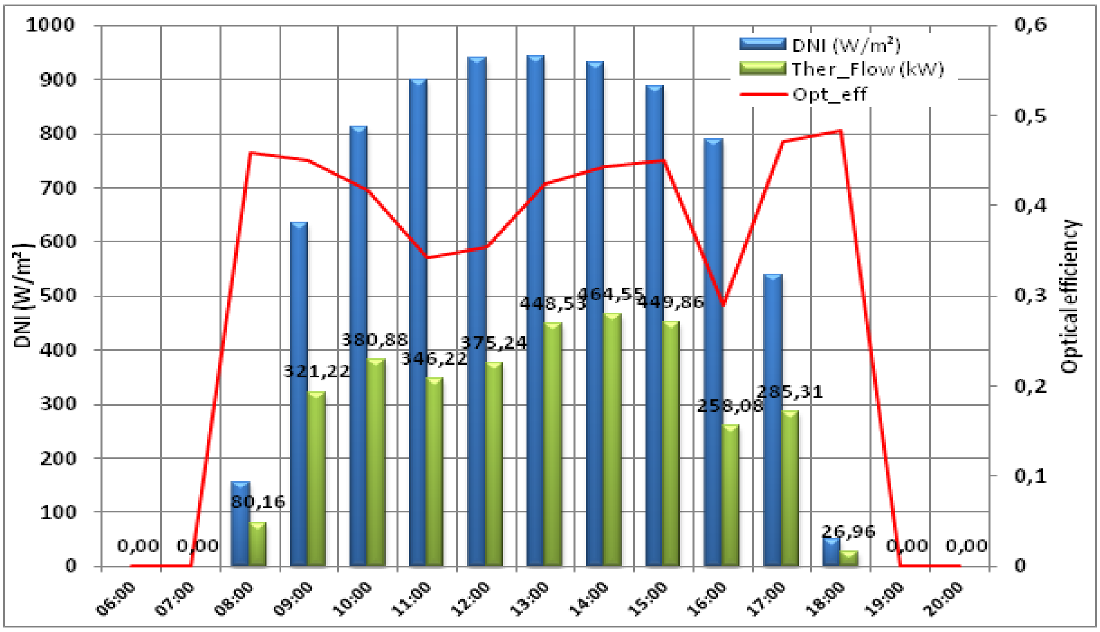



**Figure 14:** Operating condition and collector output during winter season (January 7th)

During spring season, the sunrise is relatively earlier than winter; it may be at 7am nevertheless with a low DNI rate which is not sufficient to operate the collector. However, the LFSC is more efficient at noon it generate 530kW of thermal flow transferred to the working fluid.

In addition, the optical efficiency is more important, it is higher than 0.6 during operating hours.

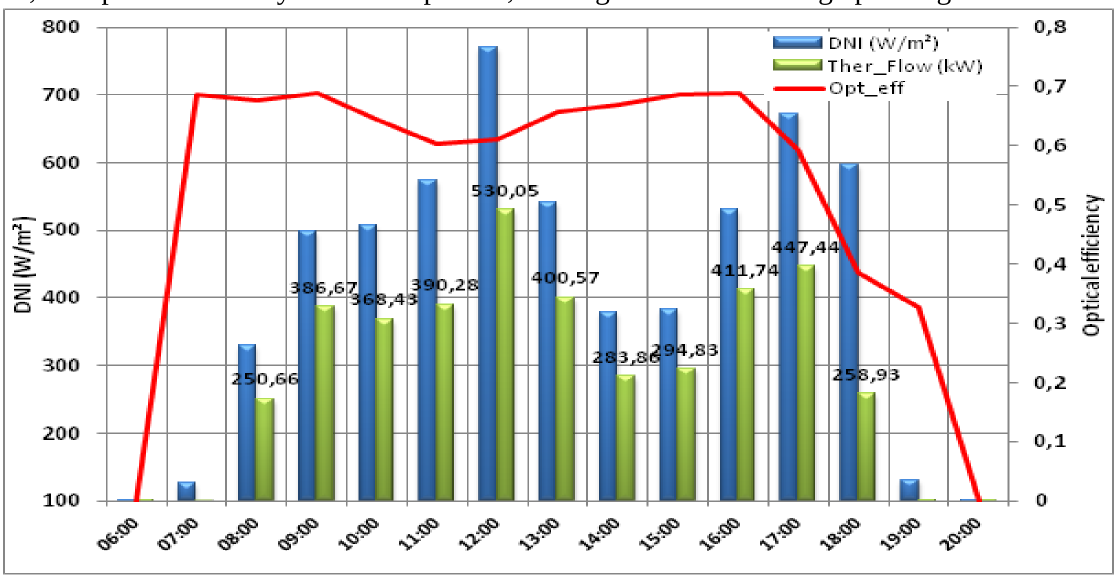



**Figure15:** Operating condition and collector output during spring season (April 7th)

The third day is chosen to be in summer. During this season, Tunisia benefits of long sunny hours which offer a good operation condition of the LFSC; it may operate during 12 hours.
With high DNI values (greater than 600W/m²), the collector is able to generate an important thermal flow (>700kW).
Concerning the optical efficiency, simulation results show that it is important during operation hours, greater than 0.7. This is due to the fact that the summer daily sun motion does not cause significant optical losses, the incident angle is low and it is close to zero at noon.

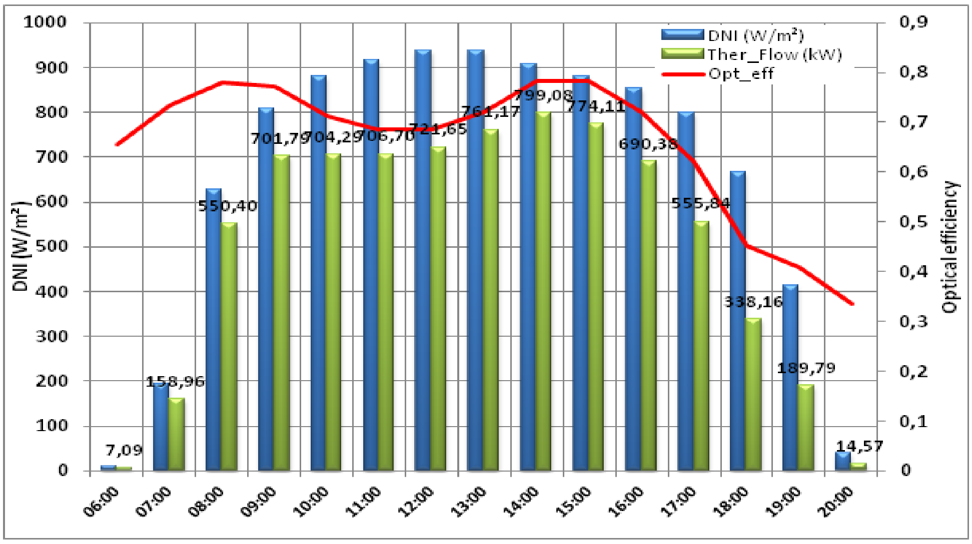



**Figure16:** Operating condition and collector output during summer season (July 7th)

Autumn climate offers also a good operation conditions, it may reach 10 efficient operating hours with a thermal flow in the range of 500kW.

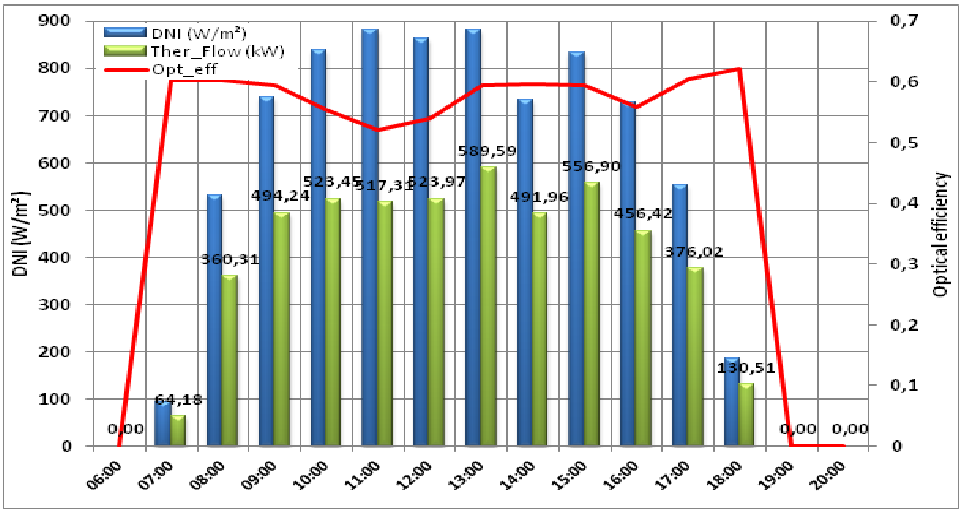



**Figure 17:** Operating condition and collector output during autumn season (October 7th)

*3.9 Annual simulation results*
As mentioned in a previous section, the optical losses generated by the primary mirror field had a big influence on the overall optical efficiency compared to optical errors produced by the secondary mirror.
In addition to the daily sun motion, there are different factor which influence the optical performance of the solar collector such as the direct normal irradiation.
The figure below shows the monthly average operating time of the LFSC under Tunisian climatic conditions. The DNI vary from 0W/m² at night to some hundreds W/m² at noon, based on the minimum DNI value needed to operate a typical LFSC, the percentage of the monthly operating hours is calculated. The Direct Normal

Irradiance in W/m² values are measured with Kipp&Zonen CHP1 pyrheliometer in enerMENA High-Precision Meteorological Station located in the southern Tunisia, in Tataouine.
The solar energy potential in Tunisia is very important, the percentage of operating hours vary from 49.56% in December to 93.54% in August. The annual average operating hours is 70.17% with regard to the total sunny hours.
During a summer day the DNI is high, it may exceed 700W/m² at noon, the sunny hours are greater than 12h which offer good condition to operate the LFSC.

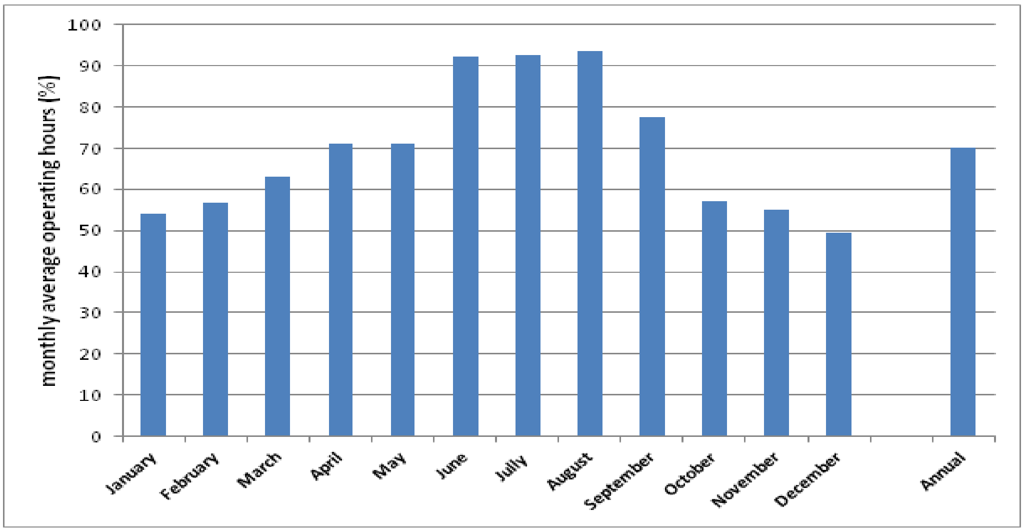



**Figure18:** Monthly average operating hours of the LFSC under Tunisian climatic conditions

The solar coordinates depend on both earth motions: the motion of the earth around the sun and around itself. This fact is the origin of the LFSC overall optical efficiency variation from one season to another.
During winter, the sun declination is low, consequently a high incident angle. In such condition, the optical losses are more important and the optical efficiency is decreased; in the range of 0.4.
In the other hand, in summer, the sun declination is higher at noon; the incidence angle is close to zero. Therefore, optical losses are less important and the optical efficiency is greater than 0.7 during three months: May, June and July. During winter, thermal flow does not exceed 350kW, and it increases in summer to reach 718.27kW in June. The variation of thermal flow transferred to the working fluid is generated by the fact that variation of the sun position (date and time) has an influence on the shape and the density of the focal spot (the reflected radiative flow on the receiver).

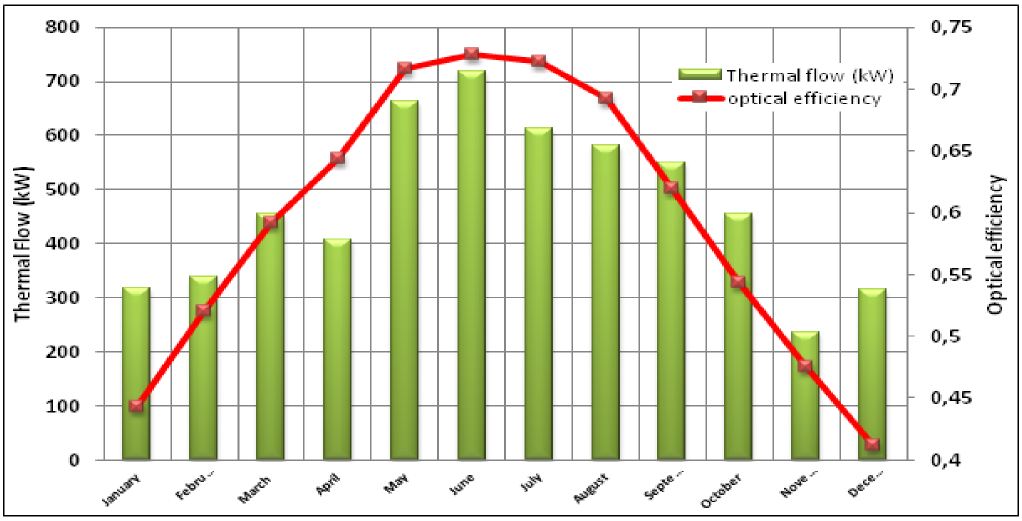



**Figure 19:** Variation of the monthly average thermal flow transferred to the working of fluid and the optical efficiency

## Conclusion

This paper discusses the impact of Linear Fresnel solar collector geometry on its efficiency. An optical modeling using a combination of both ray tracing and Monte Carlo methods is made to evaluate the influence of the geometric parameter variation on the solar energy collected on the receiver, and to simulate the influence of loss mechanisms (shading, blocking, cosine effect, end losses, etc). A linear Fresnel prototype scale is selected according to optical efficiency and power collected on the receiver. The objective of this study is to optimize all prototype parameters such as the gap between two adjacent mirrors, the number of rows and receiver height are considered as variables. Once all of parameters prototype are optimized, the new collector is then tested under different geographical parameters.

Simulation results show that:

- The optimum gap should be 10 cm in order to minimize blocking and shadowing effects and for easy maintenance and cleaning system installation. The number of mirrors stripes should be low, preferably in the range of 9 rows on each side for an optimum exploitation of supporting structure.
- Concerning the receiver height, the optimum value could be in the range of 15 m which is the limit value for the minimum of blocking and shadowing effects and spillage losses. A photon distribution on the receiver shows that a high number of photons accumulate on the center of the flat rectangle and that it decreases going far from the center. Therefore, receiver width may be reduced from 1m to 0.6 m.
- The optimum dimensions found in this study are selected according to the optical efficiency and the power collected on the receiver. The total surface of the primary mirror field is 1125 m², and the receiver surface is 30 m². The new linear Fresnel solar collector prototype has a concentration ratio equal to 37.5 %. The new prototype generates power in the order of 0.916 MW, its intercept factor is 0.795 and the optical efficiency is equal to 0.74.
- Linear Fresnel solar technology are suitable under Tunisian condition, the study of the geographical coordinates impact on the new LFSC prototype outputs prove that the variation of latitude and longitude has not a big influence on the collector power neither on the optical efficiency.
- Based on these results, we can predict solar collector efficiency, the power generated, in addition to design errors which should be avoided before the construction.
- In Tunisia, the solar energy potential is very important. The DNI is higher than that in Germany and in Spain that have already taken enormous steps towards benefiting climate friendly energy, especially the concentrated solar power plant technologies for commercial purposes. The LFSC is a promising technology in Tunisia, it can easily be adapted and implemented for process heat applications, power generation, solar cooling…

  LFSC does not require the use of a large land; its land use efficiency is very low. It can be easily integrated in building; it is also suitable for rooftop installation. Consequently, it can easily meet industry requirement.
- The solar energy potential in Tunisia is very important, the percentage of operating hours vary from 49.56% in December to 93.54% in August. The annual average operating hours is 70.17% with regard to the total sunny hours.
- Based on both the Tunisian energy status and the solar energy potential, the CSP technologies can be an attractive alternative solution, which should be encouraged by the government.

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