Research Article

Optimum Height and Tilt Angle of the Solar Receiver for a 30kWe Solar Tower Power Plant for the Electricity Production in the Sahelian Zone

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1. Introduction

The increasing use of renewable energy sources to reduce the use of fossil fuels is an essential path for the transition to a sustainable energy future with low carbon emissions [1]. Solar energy is considered the most viable renewable energy source in areas with high solar potential [2]. It can be converted into electricity in two different ways: photovoltaic (PV) and concentrating solar power (CSP) technologies [3]. The manufacture of photovoltaic technology is expensive and hardly exists in Africa. Thus, CSP technology is considered as one of the promising ways for future sustainable electricity production [4]. Among the CSP technologies, solar tower power plants (STPP) present the best performance due to their capacity to provide high temperatures and therefore high efficiency [5]. The STPP technology can be also hybridized with other energy sources and have the ability to store heat [6].

In many African countries, in particular the Sahelian zone has significant potential for the installation of STPP due to strong direct solar irradiation (DNI) of between 1400 and 2000 kWh/m²/year [7]. In addition, the electrification rate in the sub-Saharan zone is around 32% [8] on average with a strong variation from one country to another. This rate is much lower in rural areas (16%) where around 70% of the population lives [8]. The use of STPP technology can decrease this low electrification rate.

The solar field represents the key subsystem of the STPP because it contributes around 50% [9] of the total cost of the plant and causes 40% [10] of the overall energy losses. So the performance of a solar STPP depends strongly on the solar field efficiency [11]. Indeed, the solar field efficiency depends mainly on the heliostat layout in the field, the tracking system, and the control systems [11]. The optimization of heliostat layout can reduce energy losses and therefore maximize the concentrated solar flux at the input of the receiver.

Many researchers have been interested in the different categories of the heliostat layout of the solar field to find the optimal layout. Wei et al. [12] have experimented and optimized four models of heliostat field layout including north-south cornfield, north-south stagger, radial cornfield, and radial stagger. They conclude that the north-south cornfield layout is the optimal decision for the 1 MWe STPP. Zhou and Zhao [13] have presented a new method of
heliostat field layout design for two typical models: cornfield and radial stagger. The results showed an optical efficiency of 82.5% and a ground coverage of 33.6% for the radial stagger against an optical efficiency of 86.3% and a coverage of 38.3% for the cornfield. Lipps and Vant-Hull [14] have presented four categories of heliostat field layout: radial cornfield, radial stagger, north-south cornfield, and north-south stagger for a 100 MWe central receiver system. The results showed that radial staggeres are better than cornfield because they reduce the field area and increase the concentrated solar flux.

In addition, several parameters affecting the heliostat layout have been developed and optimized for maximizing concentrated solar flux. Siala and Elayeb [15] have presented a graphical method for the radial stagger layout. The heliostats are divided into groups and rings while respecting the principle of no-blocking, the safety distance ($d_s$), and the area density criteria. This method is also represented by mathematical equations thus facilitating its computer implementation. Collado [16] has developed a radial stagger layout for surrounded heliostat field which only uses two parameters for optimization, i.e., a no-blocking factor and safety distance. He confirmed that this method needs some improvement to find the optimal mean radial ($\Delta R$) and azimuthal spacing of the heliostat field. Wei et al. [17] have proposed a new method for designing the heliostat field layout for a STPP. The heliostat boundary is constrained by the receiver aperture (acceptance angle ($\delta_o$) and opening radius ($R_{out}$)) and the efficiency factor. They showed that the design time is reduced when calculating the concentrated solar flux. Zhang et al. [18] have defined a new factor called efficiency of available land. This factor is a function of atmospheric attenuation losses ($\eta_{att}$) and spilling losses ($\eta_{spil}$). It was used to position in an optimum way the heliostats of a 1 MW STPP. Its performance shows an annual optical efficiency ($\eta_{opt}$) of 71.36%. Collado and Guallar [19] have presented the details of the optimization of a large STPP like Noor III (150 MWe, 7400 heliostats) performed with theampo code [20]. They demonstrated that this code is able to optimize the heliostat field with only two parameters: the minimum ($\Delta R_{min}$) and maximum ($\Delta R_{max}$) radial spacing. This article [21] analyzes the site slope effect on the optical efficiency ($\eta_{opt}$) of the solar field. Latitude (\(\lambda\)) is treated as a control variable since it modifies all the field characteristics. This study reveals that choosing the optimal site improves optical efficiency by up to 1.65%.

The above research works are concerned with different types of heliostat layouts in the solar field and the parameters involved in the design of any heliostat layout. To our knowledge, no study has yet been carried out to assess the influence of the height and tilt angle of the solar receiver on the concentrated solar flux. The objective of the present study is to determine the optimum height and tilt angle of the solar receiver of a 30 kWe STPP intended for the production of electricity in the Sahelian zone.

To achieve this objective, the solar field is firstly sized to determine the total reflective area of the heliostats and the number of heliostats. Then, a calculation code is developed in Matlab software to determine the heliostat layout and the positions and orientations of each heliostat. Finally, we have varied the height and tilt angle of the solar receiver to determine the peak flux.

## 2. Materials and Methods

### 2.1. Solar Field Sizing.

The sizing of the solar field is done by determining the total reflecting area ($A_T$) of the heliostats. The method described in Figure 1 is suitable [4]. It consists of determining the total reflective area of the heliostats from the electrical power ($E_p$) of the STPP. This area can be determined by the following expression [4]:

$$A_T = \frac{E_p}{\eta_{opt} \cdot \eta_{rec} \cdot \eta_{conv} \cdot DNI}, \quad (1)$$

where $\eta_{opt}$ is the optical efficiency of the heliostat, $\eta_{rec}$ is the solar receiver efficiency, $\eta_{conv}$ is the conversion yield, and DNI is the direct normal irradiation in the local area.

The optical efficiency ($\eta_{opt}$) of the heliostats reflects the quantity of energy reaching the receiver following the reflection of solar rays by the heliostats [12]. It determines the set of field losses such as atmospheric attenuation ($\eta_{att}$), cosine ($\eta_{cos}$), shading and blocking ($\eta_{sh&bloc}$), reflecting ($\eta_{ref}$), and spilling losses ($\eta_{spil}$) [22].

$$\eta_{opt} = \eta_{att} \cdot \eta_{cos} \cdot \eta_{sh&bloc} \cdot \eta_{ref} \cdot \eta_{spil}. \quad (2)$$

The cosine losses represent the cosine of the angle between the incident solar ray and the vector normal to the reflecting surface of the heliostat. Therefore, they depend on both the position of the sun and the heliostat [23]. Atmospheric attenuation losses depend on weather conditions and the distance between the heliostats and the solar receiver [12]. Shading and blocking losses represent the phenomenon whereby concentrated solar rays are blocked by adjacent heliostats during scattering [24]. Spilling losses occur when the receiver cannot intercept all of the solar rays reflected by the heliostats.

The receiver efficiency ($\eta_{rec}$) is defined as the net thermal power absorbed compared to the total power intercepted at the input of the receiver. Therefore, in this definition is included the absorption losses ($\eta_{abs}$) and the conduction ($\eta_{cond}$), convection ($\eta_{conv}$), and radiation ($\eta_{rad}$) losses (see equation (3)) [4]. The conversion yield ($\eta_{conv}$) of the power unit is composed of the electrical efficiency ($\eta_{turb}$) of the micro gas turbine and the electrical generator efficiency ($\eta_{G}$) (see equation (4)) [4].

$$\eta_{rec} = \eta_{abs} \cdot \eta_{cond} \cdot \eta_{conv} \cdot \eta_{rad}, \quad (3)$$

$$\eta_{conv} = \eta_{turb} \cdot \eta_{G}. \quad (4)$$

### 2.2. Heliostat Layout Design.

Among the various heliostat layout designs mentioned above, we have adapted the radial stagger layout. This method minimizes the shading and blocking losses ($\eta_{sh&bloc}$) and represents the most widespread layout [15]. For this, the limit of the solar field shown in Figure 2 is a function of the tower’s height ($h_T$) and the
geometry of the solar receiver (acceptance angle ($\theta_a$)), inlet diameter ($R_{in}$), and tilt angle ($\beta_r$)). The acceptance angle is defined as the maximum angle according to which any ray reflected from the solar field with an incident angle ($\theta$) less than this can be received by the receiver [25]. The opening of the receiver is circular, and consequently, the limits of its projection on the solar field are described by an ellipse of semiminor axis ($a_1$) and semimajor axis ($a_2$) given by the following equations [26, 27]:

\[
a_1 = \frac{h_T \cdot \tan(\theta_a) \cdot (1 + \tan^2(\beta_r))}{1 - \tan^2(\beta_r) \cdot \tan^2(\theta_a)},
\]

\[
a_2 = \frac{h_T \cdot \tan(\theta_a)}{1 - \tan^2(\beta_r) \cdot \tan^2(\theta_a)} \sqrt{(1 + \tan^2(\beta_r)) \cdot (1 + \tan^2(\beta_r) \cdot \tan^4(\theta_a))}.
\]

In the radial stagger layout, the heliostats are divided into groups, themselves distributed in numbered rings starting from the tower. The even rings are called the essential rings, and the odd rings are called the staggered rings. This method takes into account the tilt angle of the solar field ($\beta_r$). In this method, the trajectory of a heliostat is represented by a circle as shown in Figure 3(a). Its characteristic diameter ($DM$) given by equation (7) is equal to the diagonal ($D$) of the heliostat plus the interheliostat safety distance ($d_s$) [15].

\[
DM = D + d_s.
\]

Using the dimensions of a heliostat, the characteristic diameter is written

\[
DM = \sqrt{1 + f^2 + d_s} \cdot L_h,
\]

where $f$ is the ratio between the width and the length of the heliostat and $L_h$ is the length of the heliostat.

2.2.1. Azimuthal Spacing. The azimuthal spacing in the first ring of each group representing the minimum spacing is equal to $DM$ [15]. In the other rings, the azimuthal spacing is chosen while taking care of the principle of no-blocking. For any group $j$, the azimuth angle ($\gamma_j$) can be expressed by the following relation [15]:

\[
\gamma_j = \frac{DM}{2R_{ij}},
\]

where $R_{ij}$ represents the radius in a ring $i$ and a group $j$.

The heliostats that have the same azimuth angle can be classified in the same group. The angular direction ($\Psi_m$) is an angle between the north axis and the distribution axes. It can be given by the following equation [15]:

\[
\Psi_m = \pm n \cdot \gamma_j,
\]
where \( n = 0, 2, 4, \ldots \), for the essential rings, \( n = 1, 3, 5, \ldots \), for the staggered rings, + for the northeast half field, and – for the northwest half field.

2.2.2. Radial Spacing. The radius of each ring is determined by the nature of the ring. The radius of the first ring is generally given as a function of the receiver’s height (\( h_T \)). The values proposed by Collado and Turegano [28] and Falcone [29] are generally between \( h_T/2 \) and \( h_T \). We choose \( R_{\text{min}} \) such that

\[
R_{\text{min}} = \frac{h_T}{2} + 1. \tag{11}
\]

For the second ring in any group \( j \), the radius can be expressed on a solar field inclined at an angle (\( \beta_L \)) by [13]

\[
R_{\text{min+1}} = R_{\text{min}} + DM \cdot \cos (30^\circ) \cdot \cos (\beta_L). \tag{12}
\]

So the minimum radial spacing (\( \Delta R_{\text{min}} \)) between the heliostats can be given by

\[
\Delta R_{\text{min}} = DM \cdot \cos (30^\circ) \cdot \cos (\beta_L). \tag{13}
\]

The maximum radial spacing (\( \Delta R_{\text{max}} \)) should be determined by equation (17) according to the principle of non-blocking between adjacent heliostats as shown in Figure 3(b). The detailed calculations of this principle are given by equations (14), (15), and (16) [13].

\[
z_m = R_{\text{min}} \cdot \tan (\beta_L) + H_h, \tag{14}
\]

\[
d = \sqrt{R_{\text{min}}^2 + (h_T - z_m)^2}, \tag{15}
\]

\[
\gamma = \arcsin \left( \frac{DM}{2 \cdot d} \right) + \arcsin \left( \frac{R_{\text{min}}}{d} \right) - \beta_L, \tag{16}
\]

2.3. Positions and Orientations of the Heliostats. The first step to find the position and the orientation of the heliostats in the solar field is to determine the position of the sun. The sun’s position is characterized by the altitude (\( \alpha \)) and the azimuth angle (\( A \)). Figure 4(a) shows the angles defining the apparent position of the sun. The sun’s altitude is calculated as follows [30, 31]:

\[
\alpha = \sin^{-1} \left( \sin (\lambda) \cdot \sin (\delta) + \cos (\delta) \cdot \cos (\lambda) \cdot \cos (\omega) \right), \tag{19}
\]

where \( \lambda \) is the local latitude, \( \delta \) is the solar declination angle, and \( \omega \) is the hour angle. The solar declination angle (\( \delta \)) depends on the day number (\( N \)) of the year and can be determined by [30]

\[
\delta = 23.45 \sin \left( \frac{360}{365} \cdot (284 + N) \right). \tag{20}
\]

The hour angle is measured from solar noon and is given by [30]

\[
\omega = 15 \cdot (12 - TSV), \tag{21}
\]

where TSV is the solar time. Then, the solar azimuth angle (\( A \)) representing the angle between the projection of the sun’s direction and the north direction is given by [30]
\[ A = \arcsin \left( \frac{\cos(\delta) \cdot \sin(\omega)}{\cos(\alpha)} \right). \] (22)

The sun vector \( \vec{S} \), as illustrated in Figure 4(b), can be defined by equation (23) where \( i, j, \) and \( k \) represent, respectively, the unit vectors of the \( x, y, \) and \( z \) axes.

\[ \vec{S} = S_x \vec{i} + S_y \vec{j} + S_z \vec{k}. \] (23)

By projection in the frame \( (O, i, j, k) \), the three components \( (S_x, S_y, S_z) \) of the sun vector are determined as follows [32]:

\[
S = \begin{cases} 
S_x = \cos(\alpha) \cdot \sin(A), \\
S_y = \cos(\alpha) \cdot \cos(A), \\
S_z = \sin(A). 
\end{cases}
\] (24)

A heliostat is located in the solar field by the coordinates of its center (see Figure 4(b)) which are determined once the angular direction \( (\Psi_m) \) of the heliostat and the radius \( (R) \) of the ring to which it belongs are known. Thus, the coordinates \( (H_x, H_y, H_z) \) of each heliostat can be determined by the following system of equations [13]:

\[
H = \begin{cases} 
H_x = R \cdot \sin(\Psi_m), \\
H_y = R \cdot \cos(\Psi_m), \\
H_z = H_h. 
\end{cases}
\] (25)

The cosine losses \( (\eta_{cos}) \) which represents the greatest loss in the solar field is due to the angle between the incident solar ray and the normal vector at the heliostat’s area. Therefore, it depends on both the position of the heliostat and the sun. To determine the normal vector \( (\vec{n}) \) at the heliostat’s area, the vector \( (\vec{R}) \) located between the solar receiver and the heliostat must be defined first [33].

\[
\vec{R} = \frac{\vec{T} - \vec{C}}{\| \vec{T} - \vec{C} \|}, \] (26)
where \( \vec{r} \) and \( \vec{C} \) represent, respectively, the position vectors of the sun and the heliostat. Thus, the normal vector (\( \vec{n} \)) at the heliostat’s area is given by [23]

\[
\vec{n} = \frac{\vec{R} + \vec{S}}{\sqrt{2 \cdot (1 + \vec{S} \cdot \vec{R})}}.
\]  

(27)

Then, the target vector (\( \vec{N} \)) which determines the heliostat’s position and orientation is given by

\[
\vec{N} = \vec{H} + \vec{n}.
\]  

(28)

2.4. Tilt Angle of the Receiver. The method described in Figure 5 is used to determine the optimum tilt angle of the solar receiver. This method consists of calculating the coordinates of the receiver, i.e., Aimpoint (\( X_{\text{aimpoint}}, Y_{\text{aimpoint}}, \) and \( Z_{\text{aimpoint}} \)) for different tilt angles of the solar receiver. The system of equations given by the following relation calculates the coordinates of the receiver for each tilt angle.

\[
\text{Aimpoint} = \begin{cases} 
X_{\text{ap}} = 0, \\
Y_{\text{ap}} = L_r \cdot \cos(\delta_r), \\
Z_{\text{ap}} = Z_{\text{target}} - \Delta Z,
\end{cases}
\]  

(29)

where \( Z_{\text{target}} \) is the height of the tower, \( L_r \) is the length of the solar receiver, and \( \Delta Z = L_r \cdot \sin(\delta_r) \).

2.5. Operating Parameters. We estimated the different efficiency factors that determine optical efficiency (\( \eta_{\text{opt}} \)). We have also chosen the various factors that participate in the sizing of the solar field such as the solar receiver efficiency (\( \eta_{\text{rec}} \)), the turbine efficiency (\( \eta_{\text{turb}} \)), and the electric generator efficiency (\( \eta_{\text{G}} \)). All of its operating parameters are provided in Table 1.

### Table 2: Characteristics of solar field subsystems.

| Subsystems | Parameters | Values | Units |
|------------|------------|--------|-------|
| Heliostats | Form       | Square | [-]   |
|            | Number     | 175    | [-]   |
|            | Height     | 1.50   | [m]   |
|            | Area       | 2      | [m²]  |
|            | Reflectivity | 0.90  | [-]   |
|            | Transmittivity | 0     | [-]   |
| Tower      | Orientation | North  | [-]   |
|            | Type       | Volumetric | [-] |
|            | Acceptance angle | 25     | [']   |
|            | Transmittivity | 0.90  | [-]   |
| Receiver   | Reflectivity | 0     | [-]   |
|            | Length     | 1      | [m]   |
|            | Opening radius | 0.70  | [m]   |
|            | Opening area | 1.54  | [m²]  |

3. Results and Discussion

3.1. DNI Estimate. In this study, we used direct normal irradiation (DNI) data measured in Senegal. This data is available for one year, which is acceptable for the concentrating solar power (CSP) technologies. From these data, we chose those of March 21, which corresponds to the spring equinox where the sun passes at the zenith (i.e., vertical instead). The profile of the DNI for the day of March 21 is shown in Figure 6. For the sizing of the 30kWe solar tower power plant, we chose a reference DNI of 600 W/m². This choice made it possible to obtain a solar operating range of 6h.

3.2. Result of the Sizing. For the sizing of the solar field, we chose an indirect pressurized air volumetric solar receiver with an efficiency (\( \eta_{\text{rec}} \)) of 80% [37], a Capstone turbine (C30) with an electrical efficiency (\( \eta_{\text{turb}} \)) of 26% [35], and an electric generator (\( \eta_{\text{G}} \)) yield of 90% [36]. The results showed that the optical efficiency (\( \eta_{\text{opt}} \)) of the solar field is
(a) Height of the solar tower = 20 m

(b) Height of the solar tower = 22 m

Figure 7: Continued.
(c) Height of the solar tower = 24 m

(d) Height of the solar tower = 26 m

Figure 7: Continued.
76.4% and the total reflecting area ($A_T$) of the heliostats is 350 m$^2$.

The size of the heliostats in solar tower power plants is relatively large (121 m$^2$ at PS10 and PS20) [38]. This large size of the heliostats increases mechanical stress, wind resistance, and production costs. Therefore, in this study, we chose small heliostats that could easily be handled for upkeep and maintenance. The chosen mini heliostats have a reflecting area of 2 m$^2$ and a height of 1.5 m. The surface shape of the heliostat mirror is square. So the solar field is composed by 175 heliostats. The site for the installation of the solar tower power plant is located in the department of Podor (Saint-Louis, Senegal) where the north latitude is about 16° 40’ and the west longitude is about 14° 57’.

3.3. Heliostat Layout Results. The radial stagger layout of the solar field shown in Figure 7 is designed for the 30 kWe STPP. The heliostats are placed north of the tower in the solar field. For an interheliostat security factor (ds) of 0.3, the characteristic diameter (DM) of the heliostats is 2.42 m. The minimum ($\Delta R_{\text{min}}$) and maximum ($\Delta R_{\text{max}}$) radial spacing between the heliostats are 2.1 m and 2.45 m, respectively, for the optimized coefficient of the radius ($R_{\text{coef}}$) of 0.6. The coordinates of each heliostat, the azimuth angle ($\gamma_i$), and the radius ($R_i$) of each ring are calculated. Figure 7 shows a horizontal plane and is tilted 0° with respect to the solar receiver. The main characteristics of the solar field subsystems are provided in Table 2.

**Figure 7:** Layouts of the solar field for different heights of the tower.
the heliostat layout in the solar field for the heights ($h_T$) of 20 m, 22 m, 24 m, 26 m, 28 m, and 29 m. The characteristics of each heliostat layout are given in Table 3.

As can be clearly seen in Table 3, the semiminor ($a_1$) axis and the semimajor ($a_2$) axis increase with the height of the tower, which leads to an increase in the solar field area. However, the number of rings decreases as the height of the tower increases. This shows that the more of field area increases, the number of heliostats in a ring is high, and therefore, the number of rings decreases. The radius of the first ring depends on the tower height and that of the last ring depends not only on the tower height but also on the number of rings.

### Table 3: Characteristics of each heliostat layout design.

| Heights of the tower | 20 m | 22 m | 24 m | 26 m | 28 m | 29 m |
|----------------------|-----|-----|-----|-----|-----|-----|
| Semiminor axis ($a_1$, m) | 15.14 | 15.96 | 17.41 | 18.86 | 20.31 | 21.04 |
| Semimajor axis ($a_2$, m) | 18.72 | 18.97 | 20.69 | 22.42 | 24.15 | 25.01 |
| Field area ($m^2$) | 890.5 | 951.3 | 1132.1 | 1328.6 | 1540.9 | 1652.9 |
| Number of rings | 17 | 16 | 15 | 14 | 14 | 13 |
| Essential rings | 9 | 8 | 8 | 7 | 7 | 6 |
| Staggered rings | 8 | 8 | 7 | 7 | 7 | 7 |
| Radius of the first ring (m) | 11 | 12 | 13 | 14 | 15 | 15.5 |
| Radius of the last ring (m) | 45.68 | 44.56 | 43.44 | 42.33 | 43.32 | 41.72 |

3.4. Simulation Results. After calculating the parameters of each heliostat and their design over the field using Matlab software, an Excel file is generated indicating all the positions and orientations of the heliostats. This card is incorporated in Soltrace to indicate the positions of the heliostats, the tower, and the solar receiver as illustrated in Figure 8(a). Modelling and simulation of the solar field under Soltrace reproduce the trajectory of the solar rays and establish the concentrated flux map at the entrance of the receiver. Soltrace software takes into account the reflectivity ($\rho_{ref}$) of the mirrors and adjustment errors such as slope error ($\sigma_{slope}$) and specularity error ($\sigma_{sp}$). Assuming that the reflectivity of the mirror equals to 0.90, the transmittivity equals to 0, the slope error equals to 0.95 mrad, and the specularity error equals to 0.3 mrad. The solar receiver transmittivity is 0.90, the reflectivity is 0, the slope error is 0.9 mrad, and the secularity error is 0.2 mrad. For simulation, we launched 1,000,000 solar rays to visualize the energy flow at the input of the solar receiver. Figure 8(b) shows the visualization in the Soltrace environment of the intersections between the solar rays and the elements of the solar field (heliostats, solar receiver, and tower).

The solar flux distribution over the opening of the receiver is shown in Figure 9(a). As can be seen in this figure, the spilling losses are almost zero for an input radius ($R_{in}$) of the receiver of 0.7 m. With a direct normal irradiation (DNI)
of 850 W/m², the maximum concentrated solar flux at the input of the receiver is approximately 120 kW/m² (i.e., 184.8 kW). Figure 9(b) shows the three-dimensional (3D) flux map which clearly shows the maximum solar flux.

We studied the influence of the tower’s height ($h_T$) on the concentrated solar flux at the input of the solar receiver located at the top of the tower. For this, we varied the tower’s height from 20 to 29 m to generate the maximum solar flux (peak flux) at the input of the solar receiver. The simulation results are shown in Figure 10. As we can clearly see from this figure, the solar flux starts to increase from 131.25 kW/m² for a height of 20 m up to about 134.40 kW/m² for a height of 26 m where it begins to decrease. In this interval (20 to 26 m), the solar receiver increasingly intercepts all of the solar
rays reflected by the heliostats. But after 26 m, the spilling losses ($\eta_{spil}$) seem to appear because the solar receiver is no longer able to intercept all the concentrated solar rays. These results made it possible to choose the height of the tower of 26 m because it allows obtaining a maximum solar flux at the input of the receiver which is approximately 134.4 kW/m$^2$.

The influence of the tilt angle ($\beta_1$) of the solar receiver on the concentrated solar flux is also studied in this work. The solar receiver’s height ($h_T$) is 26 m, since it is the optimum value calculated previously. We varied the tilt angle from 0 to 90° to determine the maximum solar flux (peak flux). Figure 11 shows the simulation results obtained. The tendency is similar for the solar receiver’s height. We note an increase in the solar flux up to values between approximately 60 and 65°. After 65°, the decrease of the peak flux is pronounced. This decrease is caused by the spilling losses ($\eta_{spil}$) at the opening of the solar receiver. In addition, due to the fact that the cosine losses ($\eta_{cos}$) and atmospheric attenuation losses ($\eta_{atm}$) increase, these also lead to the decrease of the concentrated solar flux. The tilt angle is therefore an important parameter of the solar receiver which must be well chosen when it is desired to obtain the maximum solar flux. With these results, it can be concluded that the optimum tilt angle is approximately 65° which corresponds to the maximum solar flux equals to 93 kW/m$^2$ (143.22 kW).

4. Conclusion

The solar tower power plant offers interesting potential for the production of electricity in the Sahelian zone where the solar potential is high and the electrification rate remains low. The objective of this study was to determine the optimum height and tilt angle of the solar receiver of a 30 kWe STPP intended for the production of electricity in the Sahelian zone. The sizing of the solar field had given the following results: an optical efficiency of 76.4% for a reference DNI of 600 W/m$^2$, a total reflective area of the heliostats of 350 m$^2$, and a number of heliostats of 175 of 2 m$^2$ area and 1.5 m height. The simulation results showed that the optimum height and tilt angle of the solar receiver were 26 m and 65°, respectively. These results will serve as a basis for the sizing of the compound parabolic concentrator (CPC) and the modelling of heat transfers within the solar receiver.

Nomenclature

- $A_T$: Total reflecting surface area (m$^2$)
- $E_p$: Electrical power (kWe)
- $a_1$: Semiminor axis (m)
- $a_2$: Semimajor axis (m)
- $h_T$: Height of the tower (m)
- $L_h$: Length of the heliostat (m)
- $R$: Radius of the ring (m)
- $H_h$: Height of the heliostat (m)
- $N$: Day number of the year
- $L_r$: Length of the receiver (m)

| Symbol | Description |
|--------|-------------|
| $\eta$: | Efficiency |
| $\beta_1$: | Tilt angle of the receiver (°) |
| $\theta_1$: | Acceptance angle (°) |
| $\gamma$: | Solar field angle (°) |
| $\Psi$: | Azimuthal angle of heliostats (°) |
| $\lambda$: | Local latitude (°) |
| $\alpha$: | Altitude of the sun (°) |
| $\delta$: | Azimuth of the sun (°) |
| $\omega$: | Hour angle (h) |
| $\sigma_{sp}$: | Specularity error (mrad) |
| $\sigma_{slope}$: | Slope error (mrad) |
| $\rho_{ref}$: | Reflectivity |

Greek Symbols

- $\eta$: Absorption heat losses (W/m$^2$)
- $\beta$: Cosine losses
- $\delta$: Shading and blocking losses
- $\kappa$: Reflecting losses
- $\eta_{spil}$: Spilling losses
- $\eta_{ref}$: Reflected losses
- $\eta_{cos}$: Cosine losses
- $\eta_{atm}$: Atmospheric attenuation losses
- $\eta_{conv}$: Convection heat losses (W/m$^2$)
- $\eta_{rad}$: Radiation heat losses (W/m$^2$).

Abbreviations

- DNI: Direct normal irradiation (W/m$^2$)
- DM: Characteristic diameter (m)
- TSV: Solar time
- HFLD: Heliostat field layout design
- STPP: Solar tower power plant
- CSP: Concentrated solar power
- PV: Photovoltaic
- MTG: Micro gas turbine
- CPC: Compound parabolic concentrator
- MCRT: Monte Carlo ray tracing.

Data Availability

We can make data available on request. If you wish to have the data used in this study, you can contact Mactar Faye at the address mactar.faye@uadb.edu.sn.

Conflicts of Interest

The authors declare no conflict of interest.

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