Optical study of solar tower power plants

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Abstract. The central receiver technology for electricity generation consists of concentrating solar radiation coming from the solar tracker field into a central receiver surface located on the top of the tower. The heliostat field is constituted of a big number of reflective mirrors; each heliostat tracks the sun individually and reflects the sunlight to a focal point. Therefore, the heliostat should be positioned with high precision in order to minimize optical losses. In the current work, a mathematical model for the analysis of the optical efficiency of solar tower field power plant is proposed. The impact of the different factors which influence the optical efficiency is analyzed. These parameters are mainly, the shading and blocking losses, the cosine effect, the atmospheric attenuation and the spillage losses. A new method for the calculation of blocking and shadowing efficiency is introduced and validated by open literature.

1. Introduction

Central receiver system consists of a high sun-tracking mirror number which concentrates solar radiation at a focal point located on the top of a high tower [1]. The heliostat field is the central subsystem in the solar tower power plant; it contributes about 50% to the total cost [2] and causes about 47% of the annual energy losses [3]. Several studies dealt with the optimization and the design of heliostat field layout [4]. Owing to the high heliostat number, the calculation of the optical losses is an iterative process [5]. Two categories of codes have been developed; the first one is dedicated only for the optical analysis of a solar concentrating system (MIRVAL, FIATLUX and SOLTRACE). The second category (DELSOL, UHC and HFLCAL) is designed to the total optimization of the concentrating system [5,6].

Many types of losses affect the heliostat field optical efficiency, namely cosine loss, losses due to the shadowing, blocking, atmospheric attenuation and spillage losses. In this current work, a mathematical model for the analysis of the optical efficiency of solar tower power plant is proposed. To validate the new proposed method, a detailed calculation of the PS10 solar field optical efficiency is made based on optical losses with wind effects neglected [6]. Shadowing and blocking effects which are the key parameters on heliostat efficiency are the main variables targeted in this work.

2. Model description

Shading and blocking efficiency is the most expensive efficiency evaluation parameters. Several calculation methods are available in open literature such the one defined by Lipps [7], this method is called the single vertex. Another method is used by HELIOS [8]; Who used the cone optics method to evaluate the solar flux density on the receiver.
According to the number of heliostats, the simulation time is too large. In order to minimize the running time, a new method is developed in this paper based on the minimization of the numbers of equations and simplification of the used methods.

### 2.1. PS10 solar power plant

**Table 1.** PS10 parameters [10]

| Component | Parameter                  | Value  |
|-----------|----------------------------|--------|
| Location  | Latitude [°]               | 37.44  |
|           | Longitude [°]              | -6.25  |
| Heliostat | Width [m]                  | 12.84  |
|           | Height [m]                 | 9.45   |
|           | Pillar height [m]          | 5.17   |
| Tower     | Height [m]                 | 115    |
|           | Length [m]                 | 18     |
|           | Width [m]                  | 8      |
| Receiver  | Height of receiver bottom [m] | 100.5 |
|           | Inclination angle [°]      | 11.5   |
|           | Width [m]                  | 13.78  |
|           | Height [m]                 | 12     |

### 2.2. Sun position

The global coordinate system includes all geographical coordinates: Altitude, Longitude, Latitude and time. With reference to these coordinates, solar position is defined by the solar azimuth, and the solar zenith [10].

### 3. Heliostat field efficiency

The instantaneous heliostat field efficiency is the product of the instantaneous optical loss factors: cosine losses ($\eta_{\cos}$), the atmospheric attenuation ($\eta_{\text{atm}}$), heliostat reflectivity ($\eta_{\text{ref}}$), shadowing and blocking losses ($\eta_{\text{sb}}$), spillage losses ($\eta_{\text{spillage}}$) [11].

$$\eta = \eta_{\cos} \times \eta_{\text{atm}} \times \eta_{\text{ref}} \times \eta_{\text{sb}} \times \eta_{\text{spillage}}$$ (1)

#### 3.1. Cosine losses

In order to guarantee an accurate tracking of the sun path during a day, each heliostat has to change its orientation according to incident angle. The cosine efficiency is calculated as the dot product of the incident sun ray direction and the normal of the mirror surface [12].

$$\eta_{\cos} = i \times n$$ (2)

#### 3.2. Atmospheric attenuation

During its path from mirror to the receiver, reflected rays are affected by the atmospheric attenuation. Losses due to the atmospheric attenuation are function of the distance between heliostat and the receiver located on the top of the tower. Also, it depends on some weather conditions i.e. the visibility. It can be calculated as [10]:

$$\eta_{\text{atm}} = \begin{cases} 
0.99321 - 0.0001176 \times \text{dist} + 1.97 \times 10^{-8} \times \text{dist}^2 & \text{dist} \leq 1000\text{m} \\
\exp(-0.0001106 \times \text{dist}) & \text{dist} > 1000\text{m}
\end{cases}$$ (3)
3.3. Mirror reflectivity
It is the quality of reflective surface; it depends on degradation and cleanliness. In this study it is
assumed to be constant equal to 0.88 [10].

3.4. Spillage loss
A portion of reflected radiation losses its path and cannot hit the receiver. This is caused by tracking
accuracy and mirror quality. This phenomenon is called Spillage.

3.5. Blocking/Shading loss
Blocking means that the heliostat located behind its neighbour cannot reflect its entire surface to the
receiver, a portion of the reflected rays is blocked by the back side of the front heliostat. Shading is
similar to the blocking, but it affects incident rays, heliostat placed in front of its neighbour shads the
heliostat behind. A detailed description of the shadowing and blocking method calculation is presented
on the next section.

4. A new method for the blocking and shading losses

4.1. Local coordinate system
The 3D coordinate system is defined as follows: the x axis goes from west to east, y axis goes from
south to north and the z goes from the ground to the sky, it is confounded with the tower.

4.2. Heliostat coordinates
Heliostat position is defined by its Cartesian coordinates \((x_i, y_i, z_i)\). The distance between a heliostat
and the tower is calculated by equation (5). Each heliostat admits its own latitude and its own angle of
inclination.

\[
\text{hel}^{\text{position}} = \sqrt{x_i^2 + y_i^2 + z_i^2}
\]

(4)

The altitude of a heliostat \((i)\) is \(A_i\), it is defined as the angle between the horizontal planes passing
through the center of the heliostat and the reflected ray.

\[
A_i = \tan^{-1}\left(\frac{H_{\text{tower}} - z_i}{\text{hel}^{\text{position}}}ight)
\]

(5)

The angle of inclination \((B)\) is:

\[
B = \begin{cases} 
  y_i > 0, & B = \cos^{-1}\left(\frac{n_3}{n_{\text{module}}}ight) \\
  y_i < 0, & B = 90 - \cos^{-1}\left(\frac{n_3}{n_{\text{module}}}ight)
\end{cases}
\]

(6)

4.3. Blocking/shadowing
The calculation procedure for the blocking and shading efficiency can be limited only to three steps:
- Select of the heliostat neighbour: In this section, only the x and y coordinates are considered. The \(k_d\) tree method [13,14] is used to find the heliostat neighbour: it is a binary tree which aims to find the nearest neighbour.
- Reduction of the computational complexity: boundary conditions: the \(k_d\) tree outputs are 10
neighbours for each heliostat, which means a total of \((624*10)\) for the entire field. Therefore,
we need to reduce this computational complexity. The same boundary conditions declared by
M.Ewert et al. [10] are used. The number of heliostat which shad/block the actual heliostat
will be function of the sun position.
In this step, a new referential is defined; each heliostat id defined as a rectangle with a center O (0, 0, 0), therefore we can define the corner as follow:

- A (L/2; W/2; 0)
- B (-L/2; W/2; 0)
- C (-L/2; -W/2; 0)
- D (L/2; -W/2; 0)

In the case of shading, each corner will be projected over the opposite sun vector. Then we have to check if the projected point is located or not on the neighbour surface. Each surface is defined by a point (center in this case) and a normal vector. In our case the actual heliostat is defined by its center (x0, y0, z0) and its normal vector. If the projected point belongs to the actual heliostat, it should follow the formula:

\[
\begin{bmatrix}
  x_0 - x_{proj} \\
  y_0 - y_{proj} \\
  z_0 - z_{proj}
\end{bmatrix} \times \begin{bmatrix}
  n_1 \\
  n_2 \\
  n_3
\end{bmatrix} = \begin{bmatrix}
  0 \\
  0 \\
  0
\end{bmatrix}
\]  

(7)

Finally, the intersection between the actual heliostat surface and the projected surface defines the shaded area. The shading efficiency is defined as:

\[
\eta_{shd} = 1 - \frac{\text{Shaded surface}}{\text{heliostat surface}}
\]

(8)

The difference between the blocking and shading is that the blocked area is calculated on the neighbouring heliostat and the shaded area is a part of the heliostat itself.

### 5. Results and discussion

#### 5.1. Validation

The new mathematical method of optical efficiency calculation is validated based on PS10 data. PS10 solar field heliostat coordinates was generated by the Sandia code WINDELSOL1.0. Blocking and shading are calculated by projecting the heliostat neighbour along the sun direction or the reflected ray direction onto the plane of the considered heliostat [16]. In this case ten neighbours are considered in the simulation. The individual efficiency factors are detailed in the table below:

| Table 2. Individual efficiency factor of PS10 |
|---------------------------------------------|
| Efficiency | Value |
|------------|-------|
| \(\eta_{\text{cos}}\) | 0.8283 |
| \(\eta_{\text{atm}}\) | 0.9498 |
| \(\eta_{\text{ref}}\) | 0.8800 |
| \(\eta_{\text{sb}}\) | 0.9255 |
| \(\eta_{\text{spillage}}\) | 0.9926 |
Table 3. PS10 Field efficiency validation

|                                | Ref [15] | Ref[11] | New code |
|--------------------------------|----------|---------|----------|
| Cosine efficiency              | 0.824    | 0.8283  | 0.8241   |
| Atmospheric attenuation        | 0.950    | 0.9498  | 0.9500   |
| Shadowing and blocking efficiency | 0.930    | 0.9255  | 0.9218   |

According to table 2, the results are in good agreement with those published by Xiudong Wei et al. [15] and Corey J. N et al. [11].

5.2. Cosine efficiency and attenuation efficiency
After validation we achieve a parametric study to evaluate the effect of key parameters on the efficiency of the field. The PS10 parameters are considered constant in all the simulation. The simulation time is chosen, in this case, as: 1st march at 12:00 local time (Seville). The sun elevation is 39.36 and the sun azimuth is 127.30. We report in the next figure the variation of the efficiency. The color degradation indicates the range of losses: the blue color indicates the range less than 0.6 and the red one is the maximum value of efficiency greater than 0.80. The figure shows that the Eastern part of the heliostat field is less affected by the cosine losses than the western part. The individual cosine efficiency is in the range of 0.8241.

Compared to the value in the table above the error of calculation is less than 0.01%. The second figure shows the attenuation efficiency function of the distance between the heliostat and the receiver. In the case of heliostat positioned in the first ranges, the efficiency is more important (> 0.96). The individual attenuation efficiency factor is in the range of the value declared by Kistler [16].

*Figure 1.* Cosine efficiency.  
*Figure 2.* Attenuation efficiency
5.3. Shadowing and blocking efficiency
As mentioned above, the number of heliostats which shade/block the heliostat subject of our interest varies with the sun position. At low sun elevation the shadow is longer and a heliostat can affect more than one neighbour. The results show that it is also function of distance between two neighbours. In the high density section of the heliostat field where the heliostats are closest (the first rows), shadowing and blocking efficiency is greater than 0.9825 and it decreases by moving away from the tower (low density region), when it reaches 0.6847.

6. Conclusion
Power production using tower technology needs a heliostat field which consists of a big number of reflective mirrors, each one moves independently of the others, and reflects the sunlight to a focal point located on the top of a tower. The motion of the heliostats generates: shading and blocking losses which are considered to be the most important optical losses. Several studies dealt with the optimization of the optical efficiency. In this current work, a new mathematical model for the analysis of the optical efficiency is proposed. The PS10 tower power plant system (Seville, Spain) is chosen as a demonstrative prototype. The model is detailed herein and validated with the open literature. Our results are in good agreement with those published by Xiudong Wei and Corey J. Noone. A parametric study to evaluate the effect of key parameters on the efficiency of the field is achieved and showed that the development of the new method can improve the existed method used to calculate heliostat field efficiency. Once the instantaneous efficiency is calculated, a year-long efficiency calculation is needed in order to evaluate the average annual heliostat efficiency.

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**Nomenclature:**

- $\alpha$: Solar Azimuth, [$^\circ$]
- $\gamma$: Solar Zenith, [$^\circ$]
- $\eta$: Optical efficiency
- $\eta_{\text{cos}}$: Cosine efficiency
- $\eta_{\text{atm}}$: Atmospheric attenuation
- $\eta_{\text{spillage}}$: Spillage losses
- $\eta_{\text{ref}}$: Heliostat reflectivity
- $\eta_{\text{sb}}$: Shadow and blocking losses
- $\eta_{\text{shd}}$: Shadowing efficiency
- $\vec{n}$: Normal vector to the heliostat surface
- $\vec{i}$: Incident vector
- $\vec{r}$: Reflected vector
- $x_i, y_i, z_i$: Heliostat coordinates
- $x_{\text{proj}}, y_{\text{proj}}, z_{\text{proj}}$: Projected point coordinates
- $x_0, y_0, z_0$: Center coordinates
- $H_{\text{tower}}$: Tower height [m]
- hel$_{\text{position}}$: Heliostat position [m]
- $n_{\text{module}}$: Module of the n vector
- L: Mirror length [m]
- W: Mirror width [m]