Design of a Solar Power Tower Plant in Adrar, Algeria: Inspired by the Surrounding Heliostat Field in Almería, Spain

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ABSTRACT

This study presents an innovated model for computing the optical efficiency of circular heliostat fields, which was validated against Collado's model and applied to the Adrar solar tower site. The model accounts for cosine effect and atmospheric attenuation, while other optical components are assumed constant. Simulations were performed for a heliostat field with 17 rows and a blocking factor of 0.95, under clear-sky conditions. Results show that the proposed model yields a slightly higher average efficiency compared to Collado's model. For the Adrar site, the average optical efficiency on the spring equinox increases from 77.77% for the previous 130 m tower to 79.08% for a 160 m modified tower, highlighting the influence of tower height on field performance. The spatial distribution of efficiency indicates that heliostats near the north side of the tower achieve the highest efficiency, while those at the south side are less efficient due to longer reflection paths. The results demonstrate that the innovated model is a reliable tool for design optimization of solar tower fields under site-specific conditions.

I. Introduction

Solar energy has emerged as one of the most promising renewable energy sources to meet the growing demand for clean and sustainable electricity generation [1]. Among the various solar technologies, concentrating solar power (CSP) systems, and in particular solar power tower (SPT) plants, have gained significant attention due to their high efficiency and potential for large-scale deployment [2, 3]. These systems utilize a field of heliostats that track the sun and reflect solar radiation toward a central receiver located at the top of a tower, where the solar energy is transformed into thermal power and subsequently into electricity through a conventional power block [4].

The design and performance of the heliostat field is a critical factor in determining the overall efficiency and cost-effectiveness of SPT plants [5]. Various parameters, including field geometry, heliostat spacing, blocking and shading effects, cosine losses, atmospheric attenuation, and optical errors, directly influence the optical efficiency of the system [6]. While early designs, such as the PSA-Almería and PS10 plants, adopted north-field configurations due to their simplicity [7], recent studies have highlighted the potential advantages of surrounding (circular) fields, which offer improved land use, higher optical efficiency, and more uniform flux distribution on the receiver [8, 9].

Several methodologies have been proposed for the preliminary design of heliostat fields, ranging from geometric layout strategies to simplified analytical models and advanced ray-tracing simulations [10, 11]. Collado et al. proposed simplified procedures for evaluating blocking and shading effects, enabling faster estimation of field performance with acceptable accuracy [12]. Comparative analyses between conventional and alternative heliostat field configurations have also been reported, showing that optimized layouts can significantly reduce optical losses and improve the levelized cost of electricity (LCOE) [13].

Despite these advances, the blocking factor remains a key challenge in surrounding heliostat fields, particularly as field size increases. Blocking occurs when one heliostat obstructs the reflected rays from another, leading to a loss of useful reflected energy. Understanding and quantifying this effect is therefore essential for achieving optimal field configurations [14]. Previous works have addressed blocking through empirical correlations, analytical approximations, and numerical simulations, but further investigations are needed to evaluate its impact in realistic plant designs [15, 16].

The aim of this study is to evaluate a MATLAB-based method for the initial proposal solar power tower plant featuring a circular heliostat field adapted to the solar resource of Adrar in Algeria. The evaluation focuses on the average optical efficiency and its spacial distribution, illustrating the potential advantages of circular field configurations and assessing the impact of tower height modification on the optical performance. The methodology incorporates geometrical field layout ideas with simplified performance evaluation tools, taking into account the atmospheric attenuation and the cosine effect under clear-sky conditions, while assuming constant values for other optical efficiency components.

The accuracy of the model is firstly verified against Collado's 2009 reference model, after which an investigation into the influence of tower height variation, from 130 m to 160 m, on optical efficiency is conducted.

II. Mathematical Modeling

II.1. Solar Location Model

In order to compute the tower shadowing effect and the instantaneous cosine efficiency of the heliostat field; it is necessary to create the specified solar location model defined as follows [17]:

$$\delta = \frac{23.45\pi}{180} \sin\left(2\pi \frac{284+n_d}{365}\right) (1)$$

$$\alpha_s = sin^{-1}[\cos(\phi).\cos(\delta).\cos(\omega_s) + \sin(\phi).\sin(\delta)] (2)$$

$$\gamma_s = \mathrm{sgn}(\omega_s)\left|\cos^{-1}\left[\frac{\sin(\alpha)\sin(\emptyset)-\sin(\delta)}{\cos(\alpha)\cos(\emptyset)}\right]\right| (3)$$

The symbols δ , α_s and γ_s are the solar declination, solar altitude, and solar azimuth angles, respectively, all in radians. Here, ω_s is the hour angle (rad), n_d is the day of the year (day) and ϕ is the latitude angle of heliostat field (rad).

II.2. Heliostat field Layout Configuration

This model, for preliminary design of surrounding heliostat field, is designed following the rules of published works described in Refs[7-11]. We used a uniformly spaced radial staggered configuration to locate the heliostats around the tower. The data of the model are derived from PSA-Almeria solar power plant and are summarized in Table 1[8]. The first heliostat row is positioned at a radial distance equal to half of the tower's optical elevation(0.5 Ht) [7], measured from the base of the tower [18-20] . With H_t is the tower optical height. On the basis of an initial estimate of the blocking factor, the radial spacing between two rows is calculated for each heliostat as follows[9, 21]:

$$\Delta R = \left[\left(\frac{cos\omega}{cos\varepsilon_T}\right)\left(1 - \frac{(1-f_b)wr}{2wr-\left(\sqrt{1+wr^2}+ds\right)}\right)\right]LH(4)$$

In equation (4), ΔR represents the local radial increment between heliostat rows (m), wr is the width-to-height ratio (dimensionless), and LH is the heliostat height *(m)*. The blocking factor f_b (dimensionless), the incidence angle ω of the sun rays onto the heliostat surface (rad), the zenith angle ε_T of the reflecting rays from the center of the heliostat pointing to the receiver surface (rad), and the extra safety distance ratio ds (dimensionless) are used to calculate the local increment. The calculated local radial increment is compared with the minimum allowable local increment as follow[22,23]:

$$\Delta R = max(\Delta R, \Delta R_{min})(5)$$

With the minimum allowable local increment of the radius between successive rows defined as follow [9]:

$$\Delta R_{min} \approx DHs. Cos30°(6)$$

Where DHs represents the diagonal of a heliostat (m) and accounts for safety considerations.

Table 1. Input Parameters for the surrounding Heliostat Field [9]

Parameters	value
Optical tower height, Ht	130 m
Minimum field radius, R_{min}	65 m
Heliostat surface area, AH	120 m^2
Heliostat height, LH	10.95 m
Height-to-width ration, wr	1.0
Spacing-to-height ration, ds	0.3
Surface reflectivity, ρ	0.8883
Field inclination, β	0
Geographic location	PSA-Almeria

The field area is divided into concentric regions, with the heliostat azimuthal spacing in the first row of each region which is the minimum possible spacing, and is almost equal to DH_s [10]. The azimuthal spacing in the other rows depends on the divergence of the distribution axes that are determined by the azimuthal spacing in the first row [10] (Figure 1.).The constant azimuth angle increment used in a region, would be[19]:

$$\Delta\alpha_T = 2. arcsin\left[\left({}^{DH_s}/_2\right)/R_{region}\right] (7)$$

With R_{region} (m) being the radius used to build the first row of this heliostat region, this azimuth increment is maintained in the following outer rows in the same region. Thus, neighboring heliostats within a row are spaced increasingly farther apart with distance from the tower, allowing the placement of an additional heliostat between them [9, 24]. This configuration is efficient, with the first row providing a high density of heliostats, unlike the outer rows where the spacing between adjacent heliostats increases. This design reduces shading and blocking problems that can occur at low sun elevation.

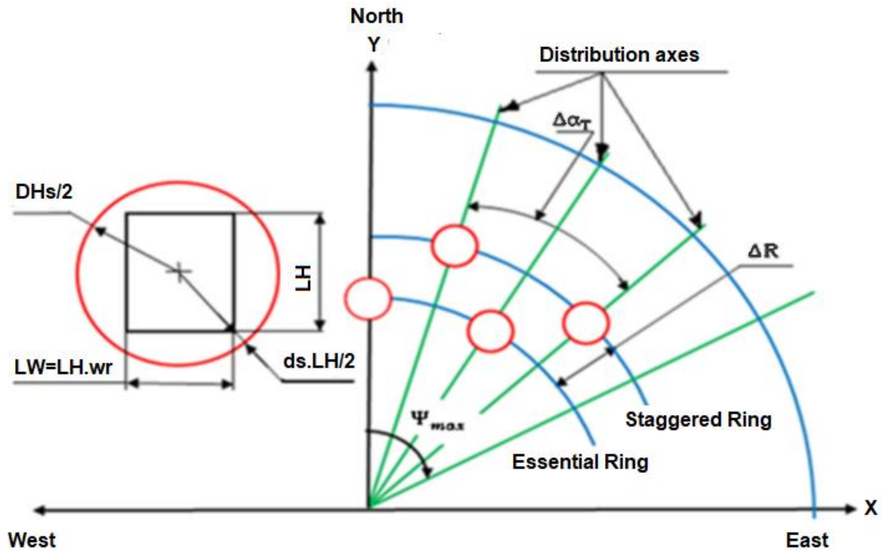


Figure 1. Main characteristics of the heliostat field[14].

II.3. Optical Efficiency

The local optical efficiency of each heliostat is given by[8] :

$$\eta_f = \rho.\cos\omega.f_b.f_{sp}.f_{at} \quad (8)$$

Where ω is the incidence angle, is calculated Following the laws of directional (specular) reflection. The dot product of unitary sun vector (pointing towards the sun) and the unit normal to the heliostat surface give us the cosine efficiency[14] .

$$\cos\omega = \overrightarrow{d_{sun}}.\overrightarrow{d_n} \quad (9)$$

ρ is the reflectivity of the mirrors and f_{sp} is the spillage factor were both assumed equal to 1, f_b is blocking factor, in this formula the shadows are neglected and f_{at} is atmospheric attenuation factor for a clear day is [15] :

$$f_{at} = 0{,}99326 - 0{,}1046.d + 0{,}0017.d^2 - 0{,}002845.d^3 \ (11)$$

Where *d (km)* is the slant range from heliostat to receiver.

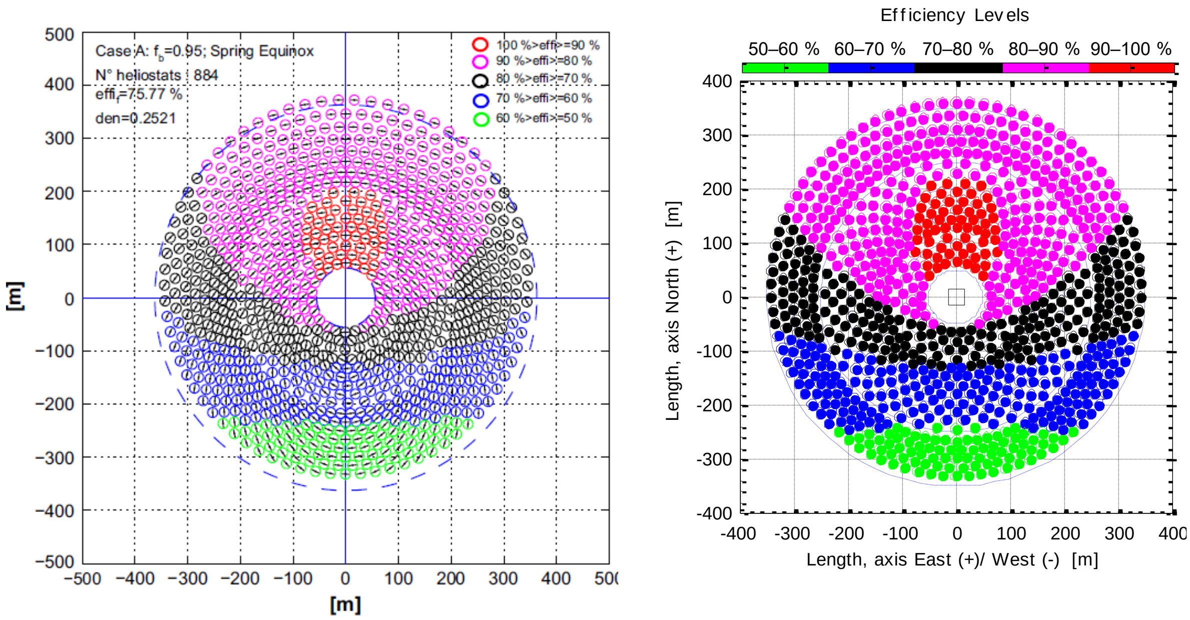
II.4. Site Selection and Justification: Adrar, Algeria

Adrar, located in southern Algeria, has been selected due to its exceptional solar and climatic conditions, such as its high Direct Normal Irradiance (DNI), exceeding 2,500 kWh/m², its predominantly clear skies, ensuring maximum solar availability, its flat terrain to facilitate heliostat field layout, and its favorable atmospheric transparency, characterized by low turbidity and minimal aerosol content [9-12]. These conditions make Adrar highly suitable for SPT deployment. By adapting the PSA-Almería plant layout to local conditions, this study aims to maximize optical efficiency and demonstrate its potential.

III. Results and Discussion

III.1. Validation of the Heliosat Field Model

To assess the accuracy of our MATLAB-based program for generating preliminary heliostat fields, we compared its results with those reported by Collado (2009) [9]. The validation was carried out for a circular field comprising 17 rows, assuming a constant blocking factor of 0.95 at the design point corresponding to the spring equinox.Figure 2 illustrates the spatial distribution of field efficiency, where Figure 2(a) corresponds to the results reported by Collado [9], and Figure 2(b) shows those obtained in the present study. To highlight local variations, heliostat circles were color-coded according to their efficiency levels.In Collado’s model, the field extends along the north axis up to approximately 372 m from the tower, while to the south it reaches about 332 m. In the east-west direction, the extension is nearly symmetric at about 344 m on each side. This north-south asymmetry arises from the application of a constant blocking factor, which affects northern heliostats more strongly due to their inclination, leading to larger radial spacing between them.In our model, the corresponding field dimensions are slightly smaller: 366.8 m to the north, 330 m to the south, and 341 m in the lateral directions. Despite these minor geometric differences, the efficiency distribution follows the same general trend: heliostats north of the tower (red zones) exhibit the highest efficiencies, whereas those located south (green zones) show the lowest values.A quantitative comparison of the two models is summarized in Table 2.



(a) (b)

Figure 2. Heliostat field efficiency distribution with 17 rows and blocking factor 0.95 at the spring equinox, (a) Collado (2009) [9], (b) current MATLAB model.

Table 2. Field dimensions and efficiency comparison between Collado (2009) [9] and the proposed model.

Site	Models	Blocking Factor	Number of Rows	Number of Heliostats	Average Efficiency (%)
PSA, Almeria	Collado’s Model [9]	0.95	17	884	75.77%
PSA, Almeria	Proposed Model	0.95	17	868	76.27%

Collado’s model predicts a field of 884 heliostats with an average optical efficiency of 75.77%, whereas our model yields 868 heliostats and an average efficiency of 76.27%. The slight difference in heliostat number is due to rounding: the exact calculation for the innermost row gives 21.9081 heliostats, but the proposed program takes the nearest lower integer, leading to a marginally reduced total count. In terms of heliostat number, the absolute difference is 16 heliostats, corresponding to a relative error of 1.81%. For average optical efficiency, the absolute difference is about0.50%, wich correspond to a lowrelative error of 0.66%. The close agreement demonstrates the reliability of the proposed model in reproducing both the geometric characteristics of the heliostat field and its average optical efficiency. Therefore, the validated model can be confidently used in subsequent analyses of the blocking factor effect on solar field performance.A quantitative comparison of the two models is summarized in Table 2. Collado’s model [9] predicts a field of 884 heliostats with an average optical efficiency of 75.77%, whereas the proposed model yields 868 heliostats and an average efficiency of 76.27%. The difference in heliostat number is mainly due to rounding: the exact calculation for the innermost row gives 21.9081 heliostats, but the algorithm selects the nearest lower integer, leading to a slightly reduced total count. In absolute terms, the difference amounts to 16 heliostats, corresponding to a relative error of 1.81%. For average optical efficiency, the absolute difference is 0.50%, corresponding to a relative error of only 0.66%.This close agreement confirms the reliability of the proposed model in reproducing both the geometric characteristics of the heliostat field and its average optical efficiency. Therefore, the validated model can be confidently applied in subsequent analyses of the blocking factor effect on solar field performance, and it will serve as the baseline reference for the remainder of this study.

III.2. Application to Adrar Site

The validated model was applied to a circular heliostat field in Adrar, where 17 rows were specified as input in the program. Based on the field layout and spacing rules, the program automatically generated a total of 868 heliostats. The analysis focuses on the spring equinox to provide a representative snapshot of site performance.
Figure 3 shows the spatial distribution of optical efficiency across the field. Heliostats near the center at the north side of the tower exhibit the highest optical efficiency, with red-colored heliostats reaching 90-100% efficiency. Heliostats at the south side of the tower show the lowest efficiency, with blue-colored heliostats in the range of 60-70%, mainly due to longer optical paths and higher cosine and atmospheric losses. The blocking factor of 0.95 slightly reduces efficiency in dense rows, but its effect is relatively uniform across the field.

The main characteristics of the Adrar heliostat field and the resulting average optical efficiency are summarized in Table 3:

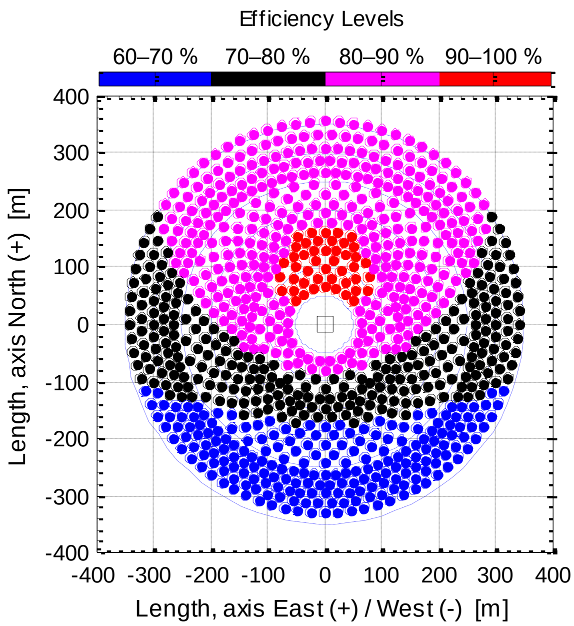


Figure 3. Optical efficiency distributionacross the Adrar heliostat field on the spring equinox

Table 3. Optical efficiency of the Adrar heliostat field on the spring equinox.

Site	Blocking Factor	Number of Rows	Number of Heliostats	Average Efficiency (%)
Adrar	0.95	17	868	77.77

These results indicate that the proposed model achieves a slightly higher average efficiency at the Adrar site compared to previous references (see Table 2). The color-coded distribution in Figure 3 further illustrates how heliostat position affects performance across the field, highlighting high-efficiency heliostats at the north side and lower-efficiency ones at the south side of the tower.

III.3. Innovated Model Validation

The innovated model was applied to the Adrar heliostat field to evaluate the effect of tower height modification on optical performance. The field consists of 17 rows, with a blocking factor of 0.95, and a tower height of 160 meters. For this analysis, only the cosine effect and atmospheric attenuation were taken into account, while all other optical efficiency components (shadowing, spillage, etc.) were assumed constant. The program calculates a total of 890 heliostats for the modified tower configuration.Figure 4 shows the spatial distribution of optical efficiency for the modified tower. Heliostats near the center at the north side of the tower exhibit the highest optical efficiency, while those at the south side show lower efficiency due to longer reflection paths and increased losses from the cosine effect and atmospheric attenuation.The average optical efficiency for the Adrar field with the modified tower is summarized in Table 4, alongside the previous configuration.

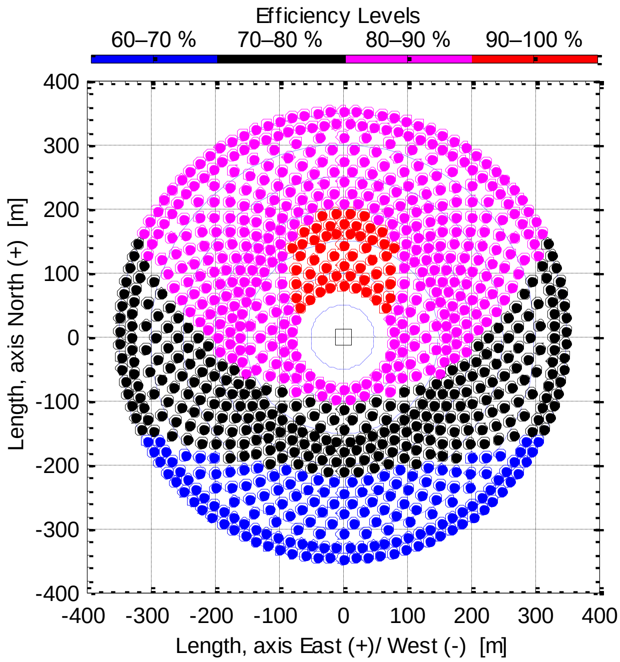


Figure 4. Optical efficiency distribution of the Adrar field with a 160 m tower height

Table 4. Average optical efficiency of the Adrar field for 130 m and 160 m towers height

Tower Height (m)	Blocking Factor	Number of Rows	Number of Heliostats	Average Efficiency (%)
Previous (130 m)	0.95	17	868	77.77
Modified (160 m)	0.95	17	890	79.08

III. Conclusion

This study presented an innovative model for evaluating the optical performance of heliostat fields validated against Collado’s model and applied to the Adrar solar tower site. A circular field design combined with a variable-height tower configuration is proposed under the specific environmental conditions of the site. The preliminary calculations indicate that the proposed model yields a slightly higher average optical efficiency compared to Collado’s model, demonstrating its capability to capture site-specific factors. This slight increase in efficiency is mainly due to a small difference in the total number of heliostats computed by the two models. The exact calculation for the innermost row gives 21.9081 heliostats, while the proposed program takes the nearest lower integer (21), resulting in a slightly reduced total heliostat count and thus a marginal increase in the average optical efficiency. For the Adrar heliostat field, the average optical efficiency on the spring equinox reached 77.77% with the baseline tower and 79.08% after increasing the tower height to 160 m, considering the cosine effect and atmospheric attenuation while other factors were kept constant. The spatial distribution of optical efficiency shows that heliostats on the north side of the tower achieve the highest performance, whereas those on the south side exhibit lower efficiency due to longer reflection paths and increased cosine and attenuation losses. Overall, the results confirm that tower height and heliostat positioning significantly affect the optical efficiency, and the proposed model provides a reliable tool for optimizing solar tower field design under site-specific conditions. The results clearly demonstrate that the objectives of the study have been fully achieved. The optical efficiency and its spatial distribution were successfully quantified for the Adrar heliostat field using a validated MATLAB-based model. Furthermore, the influence of tower height modification was confirmed to significantly affect system performance, highlighting the relevance of assessing design parameters for circular heliostat fields in high-solar-resource regions. These findings provide strong evidence supporting the adoption of circular field configurations in Algeria. Future work may incorporate additional optical factors, such as shadowing and spillage, and extend the analysis to different sites and seasonal variations to further enhance heliostat field performance.

Authors contributions:

Messaoud Bouamra : Project administration, Supervision, Visualization, Conceptualization, Data curation, Formal analysis,Investigation, Methodology, Project administration, Software, Validation, Writing – original draft, Review &Editing. **Ahmed Dahia**: Supervision, Visualization, Investigation, Formal analysis,Visualization, Writing, Review & Editing. **Youcef Bouamra** :Writing – original draft,Review & Editing,

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