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Angular Extent of the Heliostat Field in Solar Tower

Indranil Paul[1,*] and Shireesh B. Kedare[1]

[1]Department of Energy Science and Engineering, Indian Institute of Technology Bombay, India

*Correspondence: Indranil Paul, paul.indranil@iitb.ac.in

Abstract. In solar tower systems, the mirrors located on the ground reflect and concentrate the solar radiation on the receiver to increase the enthalpy of the heat transfer fluid. The mirrors can be placed surrounding the tower or limited in a direction, based on which the receiver is chosen to be external or cavity type, respectively. The overall performance of the system largely depends on the choice of the arrangement of the mirrors and the choice of the receiver. In this study, the angular extent of the heliostat field around the tower is studied at different latitudes. The field domain is discretized into square grids. The cosine and the attenuation efficiency are evaluated based on the position of the grid element and the aim point. The receiver aperture is idealized to be the outer surface of a cone and is denoted by the tilt angle. The interception efficiency is predicted with the angle made by reflected radiation on the slanted receiver aperture surface. No specific dimension for the heliostat is assumed and the amount of mirror area is expressed with the help of mirror density, which facilitates the prediction of the shading and the blocking efficiency. The amount of mirror area in each discretized field location is optimized for maximizing the optical performance. The results indicate that, with increased latitude in the northern hemisphere, the heliostat field tends to be limited towards the northern direction.

Keywords: Heliostat Field Layout, Angular Extent

1. Introduction

The solar tower system is seen as one of the most potential technologies to meet the thermal requirements of various industries and sustainably mitigate carbon emissions. Developing the solar tower system is capital intensive, which puts a premium on ensuring the maximum possible performance of each sub-system. The performance of the solar tower depends on the ability of the optical subsystem to concentrate the incoming solar radiation on the receiver and subsequently, on the capability of the receiver cooling fluid to extract the heat.

The optical subsystem consists of the heliostat field and the receiver aperture. The optical efficiency of the system is the fraction of the incoming solar radiation that is intercepted by the receiver aperture after being concentrated by the heliostat field. Several studies have been conducted to optimize different design variables of the optical subsystem with the target of maximizing the optical performance and/or reducing the cost of produced energy. Optimization of geometric variables has been performed to optimize the heliostat layout in the field for maximizing the annual optical performance of the PS10 power plant, Seville, Spain, or Gemasolar power plant, Seville, Spain by multiple researchers [1, 2]. Numerical studies have been conducted to find the best heliostat size or the optimum mix of heliostat sizes for the aforementioned power plant configurations to maximize the annual optical performance [3, 4]. For the Gemasolar power plant, the receiver dimension and the heliostat field layout variables have been optimized to improve the annual optical performance and to study the effect on the levelized cost of electricity [5, 6].

Literature review indicates that an ample amount of research work has been conducted to develop methodologies for the optimization of several design variables relating to heliostat field layout and/or receiver design variables. Although one or more of the important design variables such as the heliostat size, the receiver dimension, the receiver aperture tilt angle, and the receiver acceptance angle have been kept exactly equal to the power plant considered. It is worth pointing out that, the outcome of the studies may have been affected by the choice of the design variables that are kept constant.

The choice of the receiver depends on the layout of the heliostat field. Whereas an external type receiver is to be employed for a surrounding heliostat field; the directional type heliostat field can be coupled with a cavity type receiver. The cavity type receiver reduces the radiative and convective heat losses for having a small aperture opening to the environment. Additionally, the stagnation effect of hot air inside the cavity volume for a tilted cavity aperture reduces the convective heat loss to the environment [7]. Therefore, the optimal distribution of the mirror area in the heliostat field is of paramount importance from the optical and thermal performance perspective. In this study, a generic approach has been taken to understand the optimal distribution of the mirror area, and the tilt angle of the receiver aperture ensuring maximum optical performance of the system. Particular dimensions for the heliostat and the receiver aperture have not been assumed. The angular extent of the heliostat field is studied for a range of latitudes and tower heights in this work.

2. System description

The field domain is discretized into a grid of square shaped elements. The receiver aperture is located at an elevation equal to tower height (h) from the ground level. The receiver aperture is idealized to be the outer surface of a cone with half angle α, which is the tilt angle. The discretization of the heliostat field and the tilt angle of the aperture facilitated the calculation of the cosine, the attenuation, and the interception efficiency [8].

2.1 Mirror density

The shading and the blocking efficiency can be estimated using the mirror density, which depends on the ratio of the projected ground area to the projected mirror area towards an observer positioned along the solar radiation (reflected radiation) for shading (blocking) [9]. The mirror area in each discretized field location is expressed with the mirror density rather than considering any specific dimension for the heliostats in this work.

$$\eta_{sh} = sin\,\alpha_s/(\sigma \cdot cos\,\theta) \tag{1}$$

$$\eta_{bl} = sin\,\alpha_t/(\sigma \cdot cos\,\theta) \tag{2}$$

where the angle of incident radiation with the mirror normal is denoted by θ. The elevation angle of the sun and the elevation angle of the aim point from the heliostat are denoted by α_s and α_t, respectively. At each discretized field location, mirror density σ denotes the ratio of the mirror area (ΔA_m) to the ground area (ΔA_g). The field domain is discretized into a grid of 25 m × 25 m following a detailed sensitivity study. Thus, each ground area element has an area (ΔA_g) of 625 m^2.

$$\sigma = \Delta A_m/\Delta A_g \tag{3}$$

2.2 Optical performance modeling

The annual optical efficiency of the heliostat field is the ratio of the annual energy concentrated on the receiver over the year and the annual solar radiation energy available on the heliostat mirrors.

$$\eta_{field} = E_{ann,field} / E_{ann,avl} \tag{4}$$

where the field optical efficiency for the given heliostat field is denoted by η_{field} and N_{loc} is the number of field locations that constitute the heliostat field. The amount of solar radiation energy available on the mirrors over the year is given by Eq. (5).

$$E_{ann,avl} = \sum_{j=1}^{N_{loc}} \left(\sigma_j \cdot \Delta A_g \cdot I_{bn} \cdot \Delta t \cdot N_{ins}\right) \tag{5}$$

$$E_{ann,field} = \sum_{j=1}^{N_{loc}} E_{ann,j} \tag{6}$$

The total annual energy concentrated on the receiver aperture by all the field locations is the addition of annual energy ($E_{ann,j}$) of each field location given by Eq. (6). The time interval between two instants of calculation is denoted by Δt and taken as 4 minutes in the study. For the calculation of insolation un-weighed field optical efficiency, the beam normal radiation I_{bn} is assumed to be constant for all time instants. The annual energy concentrated on the receiver by a field location is the addition of the energy collected over all the time instants.

$$E_{ann,j} = \left(\eta_{loc,j} \cdot \sigma_j \cdot \Delta A_g \cdot I_{bn} \cdot \Delta t\right) \cdot N_{ins} \tag{7}$$

where "j" denotes the index of a particular field location. The amount of ground area associated with the mirror density σ_j is denoted by ΔA_g. The multiplication of ΔA_g and σ_j indicates the amount of mirror area. The insolation un-weighed annual optical efficiency for a given field location is termed as the local optical efficiency in this work and is denoted by η_{loc}.

$$\eta_{loc} = \sum_{1}^{N_{ins}} \eta_{ins} \Big/ N_{ins} \tag{8}$$

The simulation has been conducted for N_{ins} time instants over the year, at Δt = 4 minutes time interval. The instantaneous optical efficiency of an individual heliostat is the ratio of radiation focussed on the receiver aperture to the solar radiation intensity at that time instant. The instantaneous optical efficiency depends on the reflectivity of the mirror (ρ), the cosine (η_{cos}), the attenuation (η_{atn}), the interception (η_{int}), the shading (η_{sh}), and the blocking (η_{bl}).

$$\eta_{ins} = \rho \cdot \eta_{cos} \cdot \eta_{atn} \cdot \eta_{int} \cdot \eta_{sh} \cdot \eta_{bl} \tag{9}$$

In this work, an ideal situation is assumed with $\rho = 1$. The cosine efficiency denotes the effective mirror area intercepting the incoming solar radiation. The attenuation loss can be predicted with sufficient accuracy based only on the distance of the aim point from the heliostat

[10]. The angle made by the reflected radiation from a heliostat with the receiver aperture normal is denoted by ϕ in this work. The interception efficiency is predicted with the help of the image spread on the receiver aperture in the vertical direction only [8].

$$\eta_{int} = cos\,\phi \tag{10}$$

3. Methodology

The local optical efficiency of a field location depends on the mirror density, as the shading and the blocking efficiency are functions of it. Optimal distribution of the mirror density is required to achieve maximum optical and system performance of solar towers. Using the values of $E_{ann,avl}$ and $E_{ann,field}$ from Eq. (5) and Eq. (6) respectively, the objective function of the optimization code has been derived for a given total mirror area and given by Eq. (11).

$$OF{:}\,max \sum_{j=1}^{N_{loc}} \left(\sigma_j \cdot \eta_{loc,j}\right) \tag{11}$$

3.1 Mirror density optimization

The local optical efficiency at each grid element is calculated for discrete values of the mirror density and the generated matrix is used as the input to the optimization program developed in the MATLAB software. The optimization routine is divided into 2 segments – primary construction of the field, and iterative procedure of allocating mirror density. In the primary stage, the maximum local optical efficiency of each field location and the corresponding local mirror density is chosen. Following that, the required total mirror area (A_{mirror}) is constructed by selecting the best field locations in terms of local optical efficiency and maintaining the constraint of A_{mirror}.

In the iteration stage, the changes to the objective function for the addition and the subtraction of the mirror density for each of the primarily selected field locations are evaluated. The iterations proceed in the following method:

1. Mirror density is added to field location which increases the numerator of Eq. (4) by the maximum extent
2. Mirror density is removed from the field location which reduces the numerator of Eq. (4) by the minimum extent

The optimization program in this way removes the mirror area from one field location having low optical performance potential and assigns the mirror area to the high optical performance field location, in each iteration. After each iteration, the field optical efficiency is calculated for the new mirror density distribution.

The convergence of the optimization routine is dependent on two criteria. The primary criterion is the minimum improvement in the field optical efficiency, and the secondary is the minimum increase in the average mirror density. In the current study, the value of these parameters has been decided to be 10^{-4} and 10^{-2} respectively.

3.2 Angular extent of the heliostat field

For a heliostat field with optimal mirror density distribution, the angle made between the easternmost heliostat location and the westernmost heliostat location via north having tower base as the center is termed as the angular extent of the heliostat field. In this study, the angular extent of the heliostat field is denoted by γ_{field}. Therefore, a heliostat field with $\gamma_{field} \leq 180°$ would be limited towards the northern direction and can be identified as a directional field.

4. Results and discussion

The local optical efficiency of a field location is a function of the tower height, the latitude, and the tilt angle of the aperture. Therefore, the optimal mirror density distribution becomes a function of these variables too. Parametric study and optimization are performed for different tower heights (*h*) and latitudes while the tilt angle of the aperture is varied between 0-90°. For every latitude and tower height combination, the mirror density is optimized for all 91 values of the tilt angle. The tilt angle at which the maximum field optical efficiency is reached is noted as the optimum tilt angle (α_{opt}).

The variation of the maximum field optical efficiency (η_{field}), the optimum tilt angle (α_{opt}), the average mirror density (σ_{avg}), and the angular extent of the heliostat field (γ_{field}) with the tower height (*h*) for a mirror field area (A_{mirror}) of 0.1 km^2 at latitude 10 °N is given in Table 1. With increased tower height, the local optical efficiency potential near the tower improves due to a combined increase in the cosine efficiency and the blocking efficiency. Therefore, a greater amount of mirror area can be allocated near the tower without a detrimental increase in the blocking loss and shading loss. Additionally, the tilt angle of the aperture can also be increased to ensure a better interception of the image for the increased mirror density near the tower. As a result, with increased tower height the field optical efficiency increases accompanied by the rise in the average mirror density. At 10 °N, the sun remains on the northern side of the east-west plane for a considerable amount of time annually. Therefore, the annual cosine efficiency of the field locations to the south of the tower is also of similar magnitude compared to the northern section of the tower. Consequently, the resulting heliostat field surrounds the tower as evidenced by $\gamma_{field} = 360°$.

***Table 1**. Variation of angular extent of heliostat field with tower height at latitude 10 °N*

h (m)	$\boldsymbol{\eta_{field}}(\%)$	$\boldsymbol{\alpha_{opt}}(°)$	$\boldsymbol{\sigma_{avg}}$	$\boldsymbol{\gamma_{field}}(°)$
50	67.76	11	0.0845	360
100	69.95	22	0.122	360
150	71.80	32	0.1473	360

To understand the effect due to the solar trajectory, the investigation is extended to higher latitude locations. Table 2 shows the variation of the maximum field optical efficiency, the optimum tilt angle, the average mirror density, and the angular extent of the heliostat field with the tower height for a mirror field area of 0.1 km^2 at latitude 50 °N.

***Table 2**. Variation of angular extent of heliostat field with tower height at latitude 50 °N*

h (m)	$\boldsymbol{\eta_{field}}(\%)$	$\boldsymbol{\alpha_{opt}}(°)$	$\boldsymbol{\sigma_{avg}}$	$\boldsymbol{\gamma_{field}}(°)$
50	73.41	06	0.0498	154
100	74.01	10	0.0608	150
150	74.25	14	0.0618	150

With increased latitude in the northern hemisphere, the trajectory of the sun becomes slanted to the southern direction from the east-west plane resulting in better annual cosine efficiency for the northern side of the heliostat field. As other optical efficiency factors have none or mild directional character, so, the local optical efficiency is dominated by the cosine efficiency. As a result of the mirror density optimization, a greater amount of mirror area is allocated to the northern section of the field due to their higher optical performance potential.

Consequently, it results in a limited view directional type field for latitude 50 °N. Fig. 1 in the following shows the optimal distribution of the mirror density for latitudes 10 °N and 50 °N. The heliostat field occupies a larger ground area at latitude 50 °N due to its lower average mirror density compared to 10 °N. The reason for this occurrence can be understood by the inability to allocate high mirror density at any northern field locations due to higher shading and blocking losses at 50 °N, compared to 10 °N.

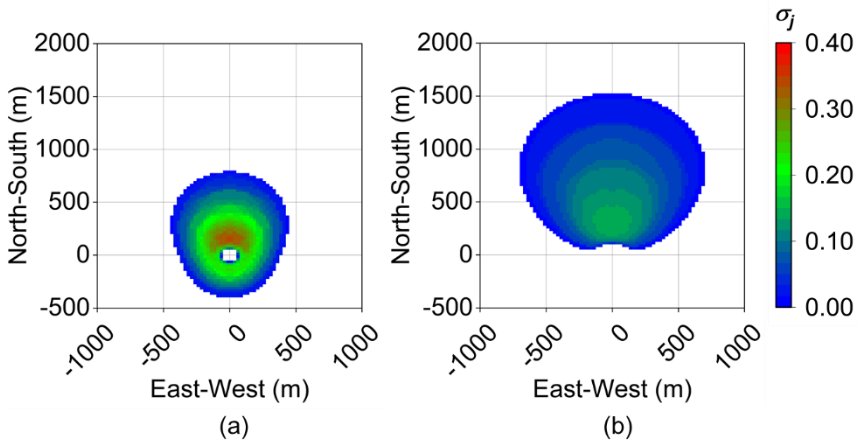

***Figure 1**. Spatial distribution of optimum mirror density for A_{mirror} = 0.1 km^2, h = 100 m at (a) latitude = 10 °N, and (b) latitude = 50 °N*

5. Conclusion

In this study, the mirror density is optimized to ensure maximum optical performance, and the angular extent of the heliostat field about the tower is studied. The optimal distribution of the mirrors depends on the latitude and the tower height. Lower latitude locations are capable of achieving a denser heliostat field requiring less ground area compared to the high latitude locations. From the outcome of the analysis, the heliostat field designer can select the number of mirrors to be placed in each field zone. The placement of mirrors can follow any particular geometric pattern like radial staggered, cornfield, Fermat spiral etc., or without any geometric pattern, as long as the optimum mirror density in the field zone is satisfied. Results indicate that an external type superficial receiver is suited for lower latitude locations as the optimized heliostat field is surround. But, with increased latitude, the angular extent of the heliostat field starts to reduce. Higher latitude locations indicate the potential of utilizing the cavity receiver with the directional type field, thus achieving a higher receiver efficiency. But the cavity type receivers impose a limit on the maximum size of the heliostat field due to their limited view angle. Thus, smaller heliostat fields with short towers and cavity receivers might be suitable for higher latitude locations. On the other hand, solar tower systems with large heliostat fields might be ideal for lower latitude locations, as superficial external type receivers can be employed.

Data availability statement

The data for this computational work can be requested via email to the corresponding author of this manuscript. Although it is the discretion and the unanimous decision of all the authors of this work to share the data of this work.

Underlying or related material

Not applicable.

Author contribution

Indranil Paul – Conceptualization, data curation, formal analysis, investigation, methodology, validation, visualization, writing – original draft

Shireesh B. Kedare – Methodology, project administration, resources, supervision, visualization, writing – review and editing

Competing interests

The authors declare that they have no competing interests

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