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Optical efficiency and optimized design of tower-type solar heliostat fields

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Abstract: *In tower solar power generation, heliostats play a pivotal role in collecting and concentrating solar energy onto receivers for thermal conversion and storage. This study addresses two critical challenges: calculating the optical efficiency of heliostat fields and optimizing mirror installation designs. An optical efficiency model has been developed, taking into account parameters such as monthly average cosine efficiency and shadow obscuration efficiency at five time points. Utilizing a simulated annealing algorithm, a nonlinear programming model is established to determine the optimal position of the absorber tower. Heliostats are arranged in a circular layout around the tower, with installation positions and quantities determined using a polar coordinate system. An optimization model computes parameters like mirror dimensions and installation height to enhance solar energy collection efficiency. This approach minimizes energy wastage, fosters sustainable development, and drives progress in the utilization of clean energy in tower solar power generation.*

Keywords: *Heliostat, Optical Efficiency, Field Design, Simulated Annealing*

1. Introduction

Tower solar thermal power generation is a new, low-carbon, and environmentally friendly clean energy technology, with heliostats serving as fundamental components for solar energy collection in tower stations. Heliostats reflect sunlight to concentrate it onto receivers mounted at the top of towers, heating the heat transfer medium within and storing solar energy in thermal form, thereby converting solar energy into heat energy.

Domestic scholars have conducted in-depth research on the calculation and optimization theory of optical efficiency in heliostat fields. For example, Zhang Ping et al. analyzed the optical efficiency of solar tower thermal power heliostat fields using geometric optics algorithms [1]. Gao Bo et al. achieved higher annual efficiency in heliostat fields through the use of a sun-tracking algorithm based on adaptive gravitational search optimization [2]. Sun Hao et al. respectively modeled and simulated heliostat fields using SolarPILOT software based on three layout patterns. They found that the mirror field had the highest annual optical efficiency and land utilization under the No blocking-dense layout [3].

Previous studies did not consider the changes in the position of the sun over time, nor did they consider the different relevant parameters of the heliostat under different conditions. This paper takes into account the changes in the position of the sun, as well as parameters such as installation height, heliostat size, and heliostat position. By establishing an optical efficiency model and applying simulated annealing algorithm, a more efficient optical energy conversion has been achieved, providing more precise and reliable design guidance for renewable energy sources such as solar energy.

2. The establishment of the model

2.1 The process of modeling the optical efficiency of heliostats

To better illustrate the geometric relationships among various variables in the modeling process, additional coordinate systems are established as follows.

2.1.1 The establishment of coordinate system

In the coordinate system centered at the focal point O of the heliostat mirror, named theheliostat mirror coordinate system, let OS represent the vector of solar light, OT represent the vector of reflected light, and ON represent the normal vector to the heliostat mirror. $\angle SON = \angle NOT = \theta$, The angle of incidence of solar light is denoted by θ. The coordinatesystem centered at the installation point of the absorber tower is called the absorber tower center coordinate system. The directions of the three coordinate axes of the two coordinate systems are shown in Figure 1.

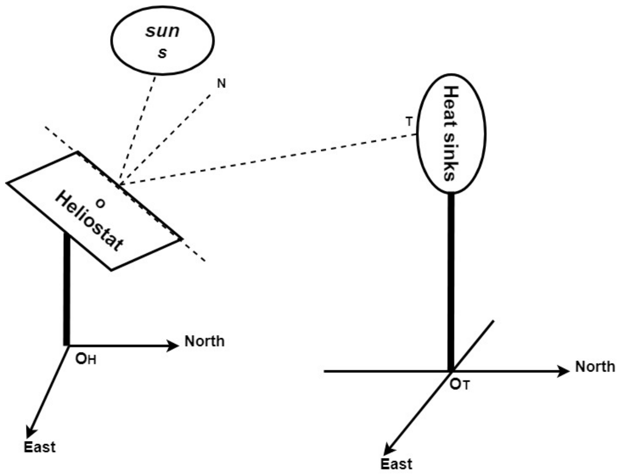

Figure 1: Central Point Coordinate System

The coordinate system for the local light collection aperture of the collector, as shown in Figure 2, is centered at the center point of the light spot, with the vertical axis representing up and down, and the horizontal axis representing sideways.

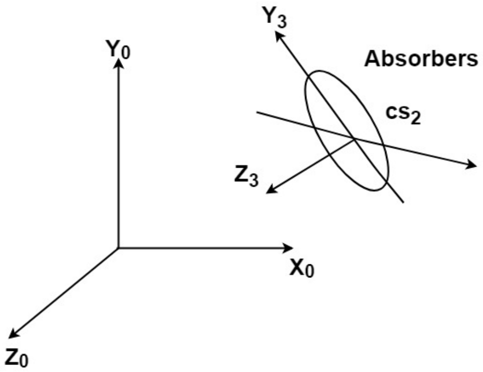

Figure 2: Local collector aperture coordinate system

2.1.2 Modeling cosine efficiency

To solve this problem, we first need to determine the angle of incidence. By using the heliostat field coordinate system, we obtain the unit vector of solar incidence light OS:

$$\vec{S} = (\cos\alpha_s \cos\gamma_s, \cos\alpha_s \sin\gamma_s, \sin\alpha_s) \tag{1}$$

where α_s is the elevation angle of the sun and γ_s is the azimuth angle of the sun.

The unit vector of vector OT:

$$\vec{t} = (\cos\alpha_t \cos\gamma_t, \cos\alpha_t \sin\gamma_t, \sin\alpha_t) \tag{2}$$

where α_t is the elevation angle between the mirror center and the absorber and γ_t is the azimuth angle between the mirror center and the absorber.

Mirror's center normal vector ON's unit vector:

$$\vec{o} = (\cos\alpha_o \cos\gamma_o, \cos\alpha_o \sin\gamma_o, \sin\alpha_o) \tag{3}$$

where α_o is the elevation angle of the mirror normal vector and γ_o is the azimuth angle of the mirror's normal vector.

Utilizing the formulas for solar altitude and azimuth calculations.

$$\sin\alpha_s = \cos\delta\cos\varphi\cos\omega + \sin\delta\sin\varphi \tag{4}$$

$$\cos\gamma_s = \frac{\sin\delta - \sin\alpha_s\sin\varphi}{\cos\alpha_s\cos\varphi} \tag{5}$$

Substituting $\vec{s}$ yields:

$$\vec{s} = \begin{bmatrix} \sin\delta\cos\emptyset - \cos\delta\cos\omega\sin\emptyset \\ \cos\delta\sin\omega \\ \sin\delta\sin\emptyset - \cos\delta\cos\omega\cos\emptyset \end{bmatrix}^T \tag{6}$$

where $\emptyset$ is local latitude, ω is hour angle and δ is solar declination angle.

$$\omega = \frac{\pi}{12}(\mathrm{ST} - 12) \tag{7}$$

where ST is local time.

$$\sin\delta = \sin\frac{2\pi D}{365}\sin(\frac{2\pi}{360}23.45) \tag{8}$$

where D is the number of days counted from the vernal equinox as day 0.

According to the principles of geometric reflection, it can be proven that the incident sunlight and the reflected sunlight are coplanar with the mirror's central normal. The mirror's central normal is centrally positioned and bisects the angle formed by the incident and reflected sunlight.

$$\angle\mathrm{SON} = \angle\mathrm{TON} = \theta \tag{9}$$

Furthermore, according to the cosine law formula:

$$\cos 2\theta = \frac{\vec{t}\times\vec{s}}{|\vec{t}||\vec{s}|} \tag{10}$$

The angle θ between the mirror and the sunlight can be determined using the cosine law formula. This angle is then used to calculate the cosine losses for each heliostat, which are then summed and averaged to obtain the cosine efficiency of the entire heliostat field.

2.1.3 The modeling of shadow obstruction losses

To address this issue, we first need to establish a coordinate system based on the absorber tower, as shown in Figure 1. Then, we can employ ray tracing techniques to resolve shadowing in the mirror field.

Assuming the coordinates of a certain target point on the mirror surface are $(x_m, y_m, 0)$. For ease of calculation, the target point coordinates are first transformed from the mirror coordinate system to the ground coordinate system, with the transformation matrix between them as:

$$M_i = \begin{bmatrix} -\sin A_H & -\cos A_H\cos E_H & \cos A_H\sin E_H & X_{gH} \\ \cos A_H & -\sin A_H\cos E_H & \sin A_H\cos E_H & Y_{gH} \\ 0 & \sin E_H & \cos E_H & Z_{gH} \\ 0 & 0 & 0 & 1 \end{bmatrix} \tag{11}$$

where A_H is the azimuth angle of the mirror center point normal vector, E_H is the elevation angle of the mirror center point normal vector and X_{gH}, Y_{gH}, Z_{gH} is The position coordinates of the mirror center point.

The coordinates of the target point of the light ray in the ground coordinate system can be obtained using Equation 11:

$$x_{mg} = -\sin A_H x_m - \cos A_H\cos E_H y_m + X_{gH} \tag{12}$$

$$y_{mg} = \cos A_H x_m - \sin A_H\cos E_H y_m + Y_{gH} \tag{13}$$

$$z_{mg} = \sin E_H y_m + Z_{gH} \tag{14}$$

By using Equations (11), (12), (13) and (14) to derive the equation of the incident light ray, which is a straight line:

$$x_g = x_{mg} - z_{mg} c\tan\alpha\cos A \tag{15}$$

$$y_g = y_{mg} - z_{mg} c\tan\alpha\sin A \tag{16}$$

According to Equation (15) and (16) we can calculate the projected coordinates of any target point on the mirror onto the ground along the direction of sunlight incidence. Consequently, we can calculate the shadow area of a single heliostat on the ground.

$$A_i = \frac{(h_w \times h_l) \cdot \cos\theta}{\sin\alpha_s} \tag{17}$$

where θ is the angle of incidence of the incident main light on the sun-tracking mirror, h_w is the width of the sun-tracking mirror and h_l is the height of the sun-tracking mirror.

The total shadow area of all mirrors on the ground can be represented by summing up the individual shadow areas:

$$\mathrm{A} = \sum \frac{(h_w \times h_l) \cdot \cos\theta}{\sin\alpha_s} \tag{18}$$

The shadow obstruction efficiency calculation formula is determined as follows:

$$\eta_{sb} = 1 - \frac{\left|\sum \frac{(h_w \times h_l) \cdot \cos\theta}{\sin\alpha_s} - \sum (h_w \times h_l)\right|}{\pi R^2 - \pi r^2} \tag{19}$$

where η_{sb} is the shadow obstruction efficiency, R is outer radius of the mirror field and r is the inner radius of the mirror field.

2.1.4 Modeling truncation efficiency

To address this issue, our strategy is to continue using ray tracing method. sunlight incidence forms a conical beam, with a half-angle divergence of:

$$\frac{\varepsilon}{2} = 4.65mrad \tag{20}$$

The sunlight incident on the mirror can be viewed as a conical beam with a vertex angle of 'ε'. Similarly, the reflection onto the absorber from the mirror also takes the form of a conical beam with the same opening angle.

Because in the local coordinate system of the light receiving aperture, we can simultaneously use the reflection light equation to establish the plane equation of the light receiving aperture, z=0. Calculate whether the reflection point falls within the plane of the light receiving aperture.

$$\begin{cases} |x_i| \leq w_r \\ |y_i| \leq H_r \end{cases} \tag{21}$$

where H_r is the height of the light aperture and W_r is the width of the light aperture.

If the reflection point is within the plane of the light receiving aperture, it's considered within the efficiency. If not, it's considered as spillage. The truncation efficiency can be calculated by dividing the sum of the number of rays falling into the light receiving aperture for each element by the total number of traced rays. The formula for calculating truncation efficiency is as follows:

$$\eta_{\mathrm{trunc}} = 1 - \frac{\mathrm{h_w \times h_l \cdot \cos\gamma_j}}{\mathrm{h_{jw} \times h_{jl} \cdot \tan\alpha_j}} \tag{22}$$

where h_{jw} is the mirror width, h_{jl} is the mirror height, r_j is the azimuth angle of the collector relative to the installation point of the sun-tracking mirror and a_j is the elevation angle of the collector relative to the installation point of the sun-tracking mirror.

The formulas for calculating atmospheric transmittance and mirror reflectance are as follows:

$$\eta_{at} = 0.99321 - 0.0001176 d_{HR} + 1.97 \times 10^{-8} \times d^2{}_{HR} (d_{HR} \leq 1000) \tag{23}$$

$$\eta_{ref} = 0.92 \tag{24}$$

where η_{at} is the atmospheric transmittance, η_{ref} is the Mirror reflectance and d_{HR} is the distance from the center of the mirror to the center of the collector.

2.2 Simulated Annealing Algorithm

The simulated annealing algorithm is a heuristic stochastic search process based on the Monte Carlo iterative method. The annealing process is controlled by a cooling schedule, which includes initial values of the control parameters t and its decay factor Δt, the number of iterations L at each t value, and the stopping condition S. In this paper, we mainly utilized its characteristics suitable for solving the

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optimization problem of the coordinates of solar collector tower positions to seek the optimal values of tower base positions.

2.2.1 The execution process of the simulated annealing algorithm

The steps for computing the optimal position of the absorber tower using the simulated annealing algorithm are as follows:

Step1: Setting initial temperature t = T = 100, termination temperature EPS 1e-1, and annealing rate DELTA = 0.95.

Step2: Randomly generate the x and y coordinates for an absorber tower, and assume that the quality of this state is the optimal solution, denoted as best Q.

Step3: Randomly generate x and y coordinates for several absorber towers to create a new state, where the quality of this state is determined by a function QQ(x, y), denoted as new Q.

Step4: If the difference between the quality of the new state and the quality of the optimal solution (diff Q) is greater than 0, or if exp(diff Q/t) is greater than a random number between 0 and 1, then.

Step5: After generating a certain number of new states randomly, update t = t * DELTA.

Step6: Termination of the algorithm occurs when the optimal solution best Q is found.

Step7: Sampling stability is achieved when t < EPS.

2.2.2 Determining the position of the absorber tower

To maximize the average annual output thermal power per unit mirror area while ensuring that the solar field reaches its rated power condition, compared to problem one, where the size and installation height of the solar concentrator mirrors remain the same, but additional parameters such as the coordinates of the absorber tower, the number of solar concentrator mirrors, the coordinates of the solar concentrator mirrors, and the installation height need to be determined. With around 2000 optimization parameters, it's nearly impossible to directly find a suitable solution using optimization algorithms. To simplify the problem, we'll model it in the following steps to find a reasonable solution.

Since the size of the site and the tower height remain constant, research indicates that a circular arrangement of solar concentrator mirrors is preferable. Therefore, we will continue to use this circular layout with other factors unchanged to calculate the optimal installation position for the absorber tower. The optimization modeling is as follows:

Decision variables: Horizontal and vertical coordinates of the new installation position for the absorber tower.

Decision objective: Maximize the average annual thermal output power per unit mirror area of the solar concentrator mirrors.

$$\textbf{Constraint conditions:}\ \ 0 \leq \sqrt{x^2 + y^2} \leq 350 \tag{25}$$

After determining the installation coordinates of the absorber tower, using the new absorber tower position as the center, and considering the maximum size of the solar concentrator mirrors (8m * 8m) as shown in Figure 3, calculate the number of concentric circles and the circumference that can be arranged. Then, for each circle, divide the circumference by the width of the mirror plus the spacing to calculate the number of mirrors that can be arranged in each circle. Summing these numbers yields the total number of solar concentrator mirrors and their installation parameters.

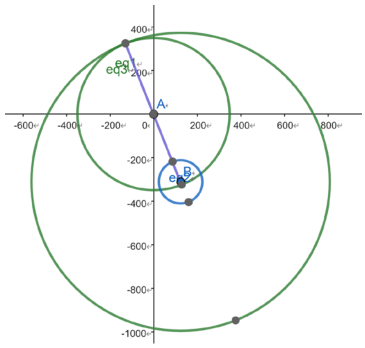

Figure 3: Diagram for the calculation of the new solar concentrator mirror.

With the number and installation positions of the solar concentrator mirrors determined, the optimization parameters are reduced to the width and height of the solar concentrator mirrors, along with the installation height. We can then utilize heuristic optimization algorithms to find the optimal mirror dimensions and installation height values.

Decision variable: Width of the solar concentrator mirror h_w, Height of the solar concentrator mirror h_l, Installation height of the solar concentrator mirror h_r.

Decision objective: Maximize the average annual thermal output power per unit mirror area of the solar concentrator mirrors.

Constraint condition: The annual average output thermal power of the solar field is greater than 60 MW.

$$2 \le \mathrm{h_w} \le 8 \quad (26)$$

$$2 \le \mathrm{h_l} \le 8 \quad (27)$$

$$\frac{\mathrm{h_l}}{2} \le \mathrm{h_w} \le 8 \quad (28)$$

3. Results

3.1 Results and Analysis of the Heliostat Optical Efficiency Model

The establishment of the solar concentrator mirror optical efficiency model is used to calculate the average cosine efficiency, shadowing efficiency, truncation efficiency, optical overall efficiency, and the average output thermal power per unit mirror area for five time points on the 21st of each month and the same day. This comprehensive calculation yields the average optical efficiency of the solar field and the annual average output thermal power per unit mirror area.

3.1.1 Analysis of experimental results

Using the formulas from references [3-5], the solar azimuth and altitude angles are calculated. Combining these angles with the shadowing loss model, truncation efficiency model, and cosine loss model, the optical efficiency of 1745 solar concentrator mirrors and the average Direct Normal Irradiance (DNI) of the solar concentrator field are computed. Using DEV-C++ software and implementing calculations in the C language, the average annual optical efficiency, annual average output thermal power, and annual average output thermal power per unit mirror area for the given problem are determined, as shown in Figure. 4.

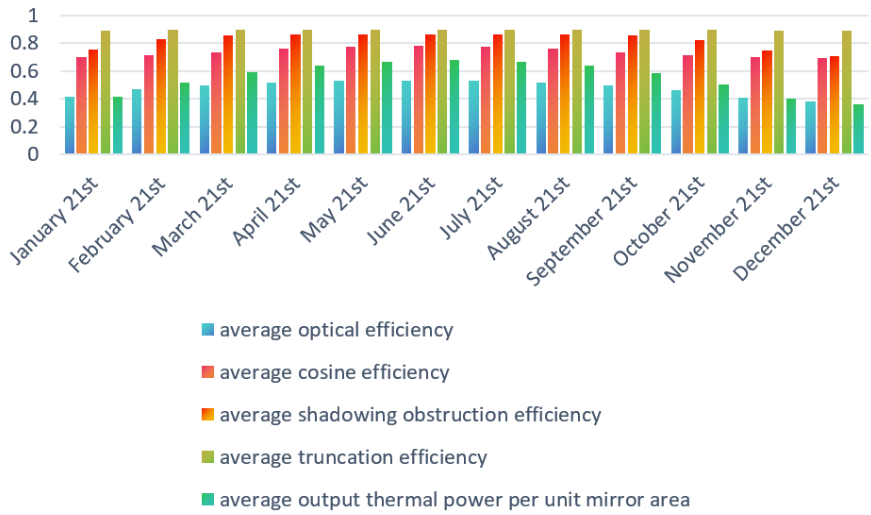

Figure 4: The average optical efficiency and output power on the 21st of each month.

Based on the monthly averages of optical efficiency, cosine efficiency, shadow shading efficiency, truncation efficiency, and unit area mirror average output thermal power on the 21st of each month, the annual average optical efficiency value is 0.47898028, the annual average cosine efficiency value is 0.73673966, the annual average shadow shading efficiency value is 0.82562448, the annual average

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truncation efficiency value is 0.89632530, and the annual average output thermal power value is 34.96440448 MW. The unit area mirror annual average output thermal power is 0.55658078 kw/m^2.

From the comparison between prediction data and actual data, it basically conforms to the reality of engineering design, and the calculated results are not significantly different from existing research conclusions. Theoretical research results and computational conclusions have certain guiding significance for the optimization design of heliostat fields.

3.2 Results and Analysis of the Simulated Annealing Algorithm Model

The objective is to maximize the annual average output thermal power per unit mirror area of the heliostat field under the condition of reaching rated power. The heliostats have the same dimensions and installation height, but include undetermined parameters such as the coordinates of the absorber tower, the number of heliostats, the coordinates of heliostat positions, and the installation height. Due to the large number of optimization parameters, around 2000, a nonlinear programming model was established based on the modeling method in heliostat optical efficiency modeling. The simulated annealing algorithm was applied to find the optimal installation position of the tower in the field.

By maintaining the circular layout of the field and using the origin of the absorber tower as the reference point, a polar coordinate system was established to calculate the circumference of concentric circles in the field, determining the mirror installation positions and numbers. Subsequently, considering mirror width, mirror height, and installation height as decision variables, another optimization model was developed. Through programming calculations, the parameters of the absorber tower's coordinates (horizontal and vertical), mirror installation height, mirror width, mirror height, and total number of mirrors were obtained as shown in Figure 5.

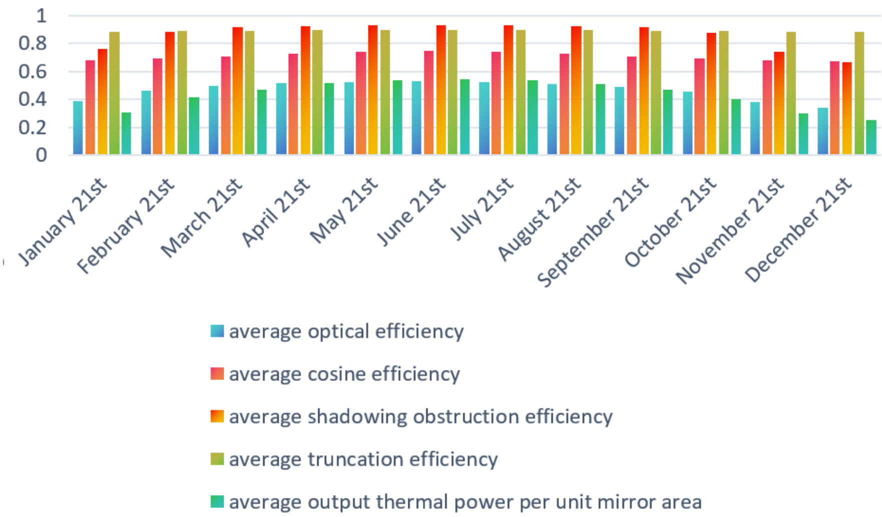

Figure 5: The average optical efficiency and output power on the 21st of each month.

Based on the monthly averages of optical efficiency, cosine efficiency, shadow shading efficiency, truncation efficiency, and unit area mirror average output thermal power on the 21st of each month, the annual average optical efficiency is 0.46754756, the annual average cosine efficiency is 0.71076875, the annual average shadow shading efficiency is 0.86737406, the annual average truncation efficiency is 0.89265715, and the annual average output thermal power is 60.00000000 MW. The unit area mirror's annual average output thermal power is 0.43818033 kW/m^2.

Establishing an optimization model and calculating through programming, the values for the absorber tower's horizontal coordinate, vertical coordinate, mirror installation height, mirror width, mirror height, and total number of mirrors are determined as 124, -312, 3.75, 8, 7.91, and 1948, respectively. With these parameters, the rated power of the heliostat field can reach 60MW.

From the comparison between prediction data and actual data, the results of the calculations closely align with engineering design realities and show minimal deviation from existing research conclusions. Theoretical findings and computational results provide valuable guidance for optimizing the design of heliostat fields.

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4. Conclusions

This paper delves into the optical efficiency and optimization engineering issues of tower-type solar heliostat fields. By establishing an optical efficiency model and simulating and optimizing the design parameters of optical systems, it achieves more efficient optical energy conversion in alignment with practical engineering designs. The computed results exhibit minimal deviation from existing research conclusions, offering valuable guidance for optimizing heliostat field designs. In the application of optical systems, it can more accurately analyze and predict the efficiency performance of the system and improve the optical efficiency by optimizing parameters. This method can be applied to various fields such as solar energy, optical communication, medical equipment, etc. Additionally, this approach can be utilized in solving optimization problems in other domains such as image processing, signal processing, and beyond.

While the simulated annealing algorithm is simple and versatile, it lacks robustness in its initial values, and the accuracy of the model in calculating shadow shading and collector truncation efficiency needs improvement. Additionally, in practical research, more factors such as environmental temperature, wind speed, wind direction, and heat losses need to be considered to better optimize the distribution of heliostat fields and enhance the overall performance of tower-type solar thermal power generation systems.

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