Research on Optimization Design of Heliostat Field Based on Multiple Models

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Abstract. This paper will optimize the heliostat field based on different models. Using quadtree model, the absorption tower is built in the center of mirror field under the preconditions of fixed size and installation height, and the annual average optical efficiency, annual average thermal output power and annual average thermal output power per unit mirror area are calculated. Based on the annealing model, the parameters of the mirror field are designed according to the rated annual average thermal output power, so that the average annual thermal output power per unit mirror area can be optimized under this condition. Through the above model, the aim of optimizing the heliostat field design is achieved, and the annual average output thermal power per unit mirror area is increased.

Keywords: Heliostat field, solar energy utilization, quadtree model, annealing model.

1. Introduction

As the global demand for clean energy continues to grow, solar energy as a non-polluting, renewable energy source has received more and more attention. In particular, heliostat systems, which produce high-temperature thermal energy by concentrating sunlight, have become a key component of solar thermal power plant technology. The heliostat system consists mainly of thousands of mirrors that accurately track the position of the sun and reflect sunlight to a receiver on a heat collector, which generates high temperatures that are further converted into electricity. Therefore, the design and optimization of heliostat field is an important step to improve the efficiency of solar thermal power station.In this study, we use several optimization models to design and optimize the parameters of the heliostat field. Firstly, the quadtree model is used to design the initial layout of the mirror field. A quadtree is a tree-like data structure that effectively divides space into four quadrants, each of which can be further subdivided as needed. In heliostatic field design, the quadtree model can be used to efficiently allocate mirror positions to ensure that each mirror can get the maximum possible sunlight, thus maximizing the heat capture efficiency of the entire mirror field.In addition, we introduced an annealing model to further optimize the mirror field design. Annealing algorithm is an optimization method that simulates the process of material heating and then slowly cooling in a physical process to achieve a lower energy state. In the heliostatic field application, the annealing model helps us find a near-global optimal solution in the mirror layout, which minimizes shadows and occlusion between the mirrors, optimizes the Angle of the mirrors to the sun, and improves the efficiency of heat capture.The application of these optimization techniques not only improves the energy conversion efficiency of the mirror field, but also reduces the construction and operation costs. With these advanced algorithms, we can achieve a more accurate and efficient mirror layout, ensuring that each mirror is working in its best position to optimize the annual average thermal output per mirror area. In addition, the optimized mirror field layout also helps to reduce land use requirements and reduce environmental impact, making solar thermal power plants more environmentally friendly and economical.This study not only shows the application effect of different optimization strategies in heliostats field design, but also provides a new idea and method for improving the efficiency of solar thermoelectric conversion and reducing the cost. In the future, these research results are expected to be applied to a wider range of solar thermal power plant projects, contributing to the global energy transition and sustainable development. Through continuous technological innovation and optimization, solar heliostat systems will continue to play an increasingly important role in the global energy market.

2. Research on the optimization of heliostat field by different models

2.1. Establishment and solution of quadtree model

In this article, we will create a quadtree to manage and query all mirror coordinates in the heliostat field, making space search more efficient, and for each mirror, calculate its shadow position at a specific sun position[4]. In this paper, various parameters are used to calculate the position of the sun relative to the heliostat on the ground at a given time and position. To calculate the shadow position of each mirror, you need to know the position of the sun, as well as the size and position of the mirror[5].

First determine the vector pointing towards the sun, the direction of this vector is determined by the sun's altitude Angle$\left(\alpha_s\right)$ and azimuth Angle$\left(\gamma_s\right)$.The unit vector of the sun can be obtained using the following formula:

$$\begin{cases} x_{sun} = \cos\left(\alpha_s\right)\sin\left(\gamma_s\right) \\ y_{sun} = \cos\left(\alpha_s\right)\cos\left(\gamma_s\right) \\ z_{sun} = \sin\left(\alpha_s\right) \end{cases} \tag{1}$$

Where x_{sun} and y_{sun} are the projections of the Sun vector in the x and y directions of the ground. z_{sun} is the component of the solar vector in a direction perpendicular to the ground. Then calculate the position of the shadow, because the shadow position of the mirror depends on the position of the sun and the size of the mirror, so:

$$\begin{cases} x_{shadow} = x_{mirror} + h_{mirror} \times \dfrac{x_{sun}}{z_{sun}} \\ y_{shadow} = y_{mirror} + h_{mirror} \times \dfrac{y_{sun}}{z_{sun}} \end{cases} \tag{2}$$

Where x_{mirror} and y_{mirror} are the coordinates of the mirror, h_{mirror} is the height or mounting height of the mirror, x_{shadow} and y_{shadow} are the positions of the mirror's shadows on the ground. Finally, calculate the length of the shadow, because the length of the shadow depends on the height Angle of the sun:

$$L_{shadow} = h_{mirror} \times \tan\left(\alpha_s\right) \tag{3}$$

Where L_{shadow} is the length of the shadow. These formulas make it possible to determine the location and length of the shadow produced by each mirror at a given time. The Sun's altitude Angle and azimuth Angle are two key parameters to describe the sun's position in the sky. The length of the shadow is inversely proportional to the height Angle of the sun. If you know the height of an object and the height Angle of the sun, the length L of the shadow can be obtained by the following formula:

$$L = \frac{h_{object}}{\tan\left(\alpha_s\right)} \tag{4}$$

Where h_{object} is the height of the object. Since the height Angle of the sun determines the length of the shadow of the object on the ground, the azimuth Angle of the sun determines the direction of the shadow. Therefore, these two parameters together determine the position and characteristics of the shadow. Using a quadtree model, query for other mirrors that may be covered by the shadow at the location of the shadow produced by each mirror. For each mirror queried, it is necessary to determine whether it is really covered by shadows. For each period of the month, the shielding loss is calculated according to the mirror area covered by the shadow, and the formula is as follows:

$$\eta_1 = 1 - \frac{s_{shadow}}{s_{all}} \tag{5}$$

Where η_1 is the shading efficiency, s_{shadow} is the total area of shading, and s_{all} is the total area of all mirrors. The cosine efficiency affects the amount of solar energy that a heliostat can capture.On specific days and times, the Sun's altitude Angle(α_s) and azimuth Angle(γ_s) are used to determine the sun's position in the sky[6].To calculate the Angle θ between the sunlight and the mirror normal, the position parameter of the sun and the mirror normal vector are used. The direction of the sun's rays can be determined by the sun's altitude Angle and azimuth Angle. These two angles describe the position of the sun in the sky.The x component of the vector is related to the solar azimuth[7]. The y component of the vector is related to the altitude Angle of the sun.Since the mirror is assumed to be mounted perpendicular to the ground, its normal vector is fixed, usually (0, 0, 1). The Angle of incidence is the Angle between the sun's ray vector and the mirror's normal vector. The following formula can be used to calculate the dot product of vectors:

$$\cos\theta = \frac{\vec{A} \cdot \vec{B}}{\left|\vec{A}\right| \times \left|\vec{B}\right|} \tag{6}$$

Where θ represents the Angle of incidence, $\vec{A}$ is the direction vector of the sun's rays, and $\vec{B}$ is the normal vector of the mirror.Since the mirror's normal vector has length 1, and the direction vector of the sun's rays is also normalized to length 1, the above formula can be simplified to:

$$\cos\theta = \vec{A} \cdot \vec{B} \tag{7}$$

Where "·" represents the dot product of vectors. Then use the inverse cosine function to get the actual value of the incidence Angle:

$$\theta = \arccos\left(\vec{A} \cdot \vec{B}\right) \tag{8}$$

Through these steps, the incidence Angle between sunlight and the mirror normal can be obtained, which is a key parameter for calculating cosine efficiency. Cosine efficiency is the cosine of the Angle between sunlight and the mirror normal, expressed as:

$$\eta_{\cos} = \cos\theta \tag{9}$$

This step only needs to use the calculated Angle of incidence. Since the position of the sun changes with the time and date, the Angle of incidence also changes[8]. In order to obtain the annual mean cosine efficiency, several representative dates and time points in a year are selected, and the cosine efficiency calculated at different dates and time points is averaged to obtain the annual mean cosine efficiency of the heliostat field. Two main factors are taken into account in calculating the truncation efficiency: the total reflected energy of the mirror and the received energy of the collector. The calculation formula of truncation efficiency is as follows:

$$\eta_{trunc} = \frac{E_{surface}}{E_{collerctor} - E_{shadow}} \tag{10}$$

Where $E_{surface}$ is the total reflection energy of the mirror, $E_{collector}$ is the energy received by the collector, and E_{shadow} is the energy lost by the shadow occlusion. In order to calculate the truncation efficiency, it is necessary to determine the intersection point of sunlight and heliostat. The intersection point of sunlight and heliostat is calculated using the position of the sun and the position of the heliostat, using the position of the sun and the position of the heliostat to calculate the intersection of sunlight and heliostat, using the sun's height Angle α_s and azimuth Angle γ_s to determine the position of the sun. At the same time, considering the (x,y) position and direction of the heliostatic mirror, the position of the heliostatic mirror is determined by its coordinates in the field, when we take into account the above factors, the calculation of the intersection point of the sunlight and the heliostatic mirror can be based on α_s and γ_s to determine the direction vector of the sunlight[9]. Then the normal direction of the heliostat is automatically adjusted and determined by the position of the sun and the design of the heliostat. The point at which sunlight intersects this plane is the point at which sunlight intersects the heliostat. It is important to note that this intersection is usually not calculated directly, but it is used to determine the direction of the reflected light. This direction is used to determine the intersection point of the reflected light and the collector, so as to determine whether a truncation has occurred[10]. Based on the sun's altitude Angle α_s and azimuth Angle γ_s, the direction vector of the sunlight can be determined, and thus the direction of the incident light can be determined. To ensure that the reflected light is directed to the center of the collector as much as possible. Then calculate the direction of the reflected light using the following formula:

$$\vec{b} = \vec{a} - 2 \times \left(\vec{a} \cdot \vec{n}\right) \times \vec{n} \tag{11}$$

Where $\vec{b}$ reflects vector, $\vec{a}$ incident vector, $\vec{n}$ normal vector here, " · " stands for the dot product of the vectors, since the collector is modeled as a cylinder standing on the ground.So first determine the equation of the reflected rays, since each ray can be represented by a point and a direction vector. Therefore, the parametric equation for a ray can be expressed as:

$$R(t) = O + t \cdot D \tag{12}$$

Where $R(t)$ is the point on the ray, O is the origin, D is the direction of the reflected ray, and H is the parameter. Then determine the equation of the collector, from the collector is a vertical cylinder to the ground, it can be seen that its equation can be expressed as:

$$x^2 + y^2 = r^2 \tag{13}$$

Where r is the radius of the collector. After calculation, the parametric equation of the ray is substituted into the equation of the collector, and the parameter t is solved.Then substitute t into the ray equation to get the coordinates of the intersection points. Verify whether the intersection is within the height range of the collector, determine the location of the intersection, and determine whether it is truncated. Then the whole heliostat field is calculated to calculate the average truncation efficiency at each moment. The formula used in this paper to calculate the optical efficiency of each heliostat is:

$$\eta_i = \eta_{sbi} \times \eta_{\cos i} \times \eta_{at} \times \eta_{trunci} \times \eta_{ref} \tag{14}$$

Where sbi is the shading efficiency of the I-th mirror; $\cos i$ is the cosine efficiency of the I-th mirror; at is atmospheric transmittance; $trunci$ is the truncation efficiency of the I-th mirror; ref is for mirror reflectivity. Use this formula to calculate the average optical efficiency of the entire site:

$$\bar{\eta} = \frac{\sum_{i=1}^{N} \eta_i}{N} \tag{15}$$

Where N is the total number of heliostats. In previous calculations, all of these efficiencies have been taken into account, including cosine efficiency, shadow occlusion efficiency, and truncation efficiency, and then the average optical efficiency of the entire site is calculated. When calculating the average annual thermal output, you need to calculate the average direct normal irradiance DNI for each month:

$$DNI = G_0\left[a + b\times\exp\left(-\frac{c}{\sin\alpha_s}\right)\right] \tag{16}$$

Where G_0, a,band c are constants that depend on altitude. Then calculate the thermal power output for each month:

$$E_{field} = DNI\times\sum_{i=1}^{N} A_i\times\eta_i \tag{17}$$

Where DNI is the normal direct irradiance. N is the total number of heliostats. A_i is the lighting area of the I-th heliostat. η_i is the optical efficiency of the I-th mirror. In order to get the total output thermal power for each month, the output thermal power of all mirrors is summed. Calculate the annual average thermal output power, take the average monthly thermal output power, so as to obtain the annual average thermal output power:

$$E_{avg} = \frac{\sum_{i=1}^{12} E_{field,i}}{12} \tag{18}$$

These steps use the provided data and formulas to calculate the average annual thermal power output. Thermal power output per unit area of mirror per month:

$$E_{field,unit,area} = \frac{E_{field}}{N\times A_{mirror}} \tag{19}$$

This simplifies the calculation because the area of each mirror is the same. Finally, the average monthly mirror output thermal power per unit area is taken to get the annual average mirror output thermal power per unit area. The results obtained from the model are shown in Table.1. and Table.2.

Table.1. Average optical efficiency and output power on 21 days per month

Date	Average optical efficiency	Average cosine efficiency	Average shading efficiency	Average truncation efficiency	Average output thermal power per unit area of mirror $\left(kW/m^2\right)$
1.21	80.90%	98.54%	92.32%	83.69%	0.802
2.21	79.73%	98.29%	91.22%	82.49%	0.817
3.21	79.16%	98.18%	90.67%	81.90%	0.824
4.21	78.98%	98.19%	90.45%	81.71%	0.825
5.21	79.86%	98.35%	91.31%	82.62%	0.831
6.21	81.52%	98.62%	92.96%	84.34%	0.837
7.21	82.98%	98.93%	94.32%	85.85%	0.822
8.21	85.61%	99.21%	97.04%	88.57%	0.799
9.21	87.38%	99.36%	98.34%	90.41%	0.756
10.21	86.87%	99.34%	96.34%	89.88%	0.724
11.21	85.20%	99.14%	96.64%	88.14%	0.740
12.21	82.62%	98.85%	93.99%	85.48%	0.774

Table.2. Annual average optical efficiency and output power meter

Average annual optical efficiency	Average annual cosine efficiency	Annual average shadow occlusion efficiency	Average annual truncation efficiency	Annual average output heat power $\left(MW\right)$	Mean annual mirror output thermal power per unit area $\left(kW/m^2\right)$
80.42%	98.75%	94.01%	99.73%	48.953	0.796

2.2. Establishment and solution of annealing model

In this paper, we also build an annealing model to describe the performance of solar heliostat field. This model includes solar altitude Angle, solar azimuth Angle, normal direct radiation irradiance and other related formulas for solar energy collection. The calculation of the optical efficiency of the mirror is also introduced, and the specific formula is as follows:

$$\sin\alpha_s = \cos\delta\cos\varphi\cos\omega + \sin\delta\sin\varphi \tag{20}$$

$$\cos\gamma_s = \frac{\sin\delta - \sin\alpha_s\sin\varphi}{\cos\alpha_s\cos\varphi} \tag{21}$$

$$\omega = \frac{\pi}{12}\left(ST - 12\right) \tag{22}$$

$$\sin\delta = \sin\frac{2\pi D}{365}\sin\left(\frac{23.45\times 2\pi}{360}\right) \tag{23}$$

Where φ is the local latitude and north latitude is positive, ω is the solar hour Angle, ST is the local time, δ is the solar declination Angle, and D is the number of days counting from the vernal equinox as day 0. Normal direct radiation irradiance DNI (unit: kW/m^2) refers to the solar radiation energy received per unit area and per unit time on the plane perpendicular to the sun's rays on the earth:

$$DNI = G_0\left[a + b\times\exp\left(-\frac{c}{\sin\alpha_s}\right)\right] \tag{24}$$

$$a = 0.4237 - 0.00821\left(6 - H\right)^2 \tag{25}$$

$$b = 0.5055 + 0.00595\left(6.5 - H\right)^2 \tag{26}$$

$$c = 0.2711 + 0.01858\left(2.5 - H\right)^2 \tag{27}$$

Where DNI is the solar constant, whose value is $366\,kW/m^2$, and H is the altitude (unit: km). The optical efficiency η of heliostat is:

$$\eta = \eta_{sb}\eta_{\cos}\eta_{at}\eta_{trunc}\eta_{ref} \tag{28}$$

$$\eta_{sb} = 1 - E_{shadow} \tag{29}$$

$$\eta_{\cos} = 1 - E_{\cos} \tag{30}$$

$$\eta_{at} = 0.99321 - 0.000117 d_{HR} + 1.97\times 10^{-8}\times d_{HR}^2\left(d_{HR}\le 1000\right) \tag{31}$$

Where mirror reflectance η_{ref} can be a constant, η_{sb} is the shading efficiency; E_{shadow} is shadow occlusion loss; $\eta_{\cos}$ is the cosine efficiency; $E_{\cos}$ is the cosine loss; η_{at} is atmospheric transmittance; d_{HR} is the distance from the center of the mirror to the center of the collector (unit:m); η_{trunc} is collector truncation efficiency.

To optimize the process, we chose the simulated annealing algorithm as the optimization tool. The simulated annealing algorithm is a heuristic algorithm used to search for the optimal configuration. It is based on an objective function, maximizes this objective function by adjusting the number, size, and position of the mirrors, discusses the possible objective functions, and then evaluates its performance using simulated annealing algorithms and iterates repeatedly until a satisfactory configuration is found. Efficiency gains can be achieved by evaluating multiple configurations simultaneously. Through the optimization of the simulated annealing algorithm, an optimal configuration is found to maximize the total output power. To determine the total heliostat area required to achieve a rated power of 60 MW, it can be estimated by the following formula:

$$DNI \times \sum A_i \times \eta_i = 60 \times 10^6 \tag{32}$$

Where A_i is the area of each mirror and η_i is the optical efficiency of each mirror. Consider that the best position for the absorber may still be the center of the heliostat field. The size and mounting height of the mirror will affect the optical efficiency. Find the combination that maximizes the average annual thermal power output per mirror area. The size of the mirror affects its number and position, calculate the number of mirrors that can be placed in the heliostat field and the specific position. Repeat the above steps until you find a satisfactory configuration. This data is used to train the model, comparing the model's predictions to the actual data, ensuring that the differences between them are within acceptable limits.

The key step to solve this problem is to determine the number and area of heliostats with the rated annual average output thermal power of $60MW$ heliostats. First, the paper need to know that the heliostat field has a rated average annual thermal output of $60MW$. Taking into account the duration of sunlight and the efficiency factor, it is possible to estimate the total energy that the heliostat needs to capture during the day. Firstly, the sun declination Angle is calculated, the sunshine duration is calculated, and the installation height is determined. The installation height can be optimized according to the cosine efficiency, shadow blocking efficiency and truncation efficiency. Since the power rating is known to be $60MW$, estimate the number of mirrors required based on this. In order to maximize the output power per unit area, the mirrors should be evenly distributed over the entire site, and ensure that the distance between the mirrors is large enough to avoid mutual influence.

After this , we need to determine the average output power of a single heliostat, which can be estimated by considering the average optical efficiency of the heliostat and the average irradiance of sunlight. The output power is determined by the optical efficiency and sunlight irradiance of the heliostat, as well as the area of the heliostat. After describing the position of the sun, the reflection characteristics of the heliostat, and the geometric relationship between the absorber and the collector, the constraints may include the size of the site, the maximum and minimum sizes of the mirror, and the range of installation heights, using numerical optimization techniques. Find the parameter values that maximize the objective function. The simulated annealing method is used to solve the problem. Possible combinations of heliostatic size are selected, optimization algorithms are used to determine the optimal placement layout, the efficiency of each layout is evaluated, and ray tracing models are used to determine the efficiency of sunlight reflected from each mirror to the collector. Calculate shadow occlusion, cosine loss, and other efficiency factors. Calculate the total output power and the annual average output thermal power per unit mirror area. Fine-tune the length and width of the heliostat, change the position of the heliostat to reduce shadow occlusion and improve efficiency, and finally set the stop criterion, and select the best performance configuration when the stop criterion is reached.

In this paper, we use simulated annealing to select the configuration with the best performance, and repeat the following steps for each temperature: Select a neighboring configuration. Calculate the performance difference between the new configuration and the current configuration. If the new configuration is better, or if certain probabilistic conditions are met, the new configuration is accepted. Finally reduce the temperature and repeat the steps until the lowest temperature is reached.

The results are obtained according to the model, as shown in Table.3., Table.4.and Table.5.

Table.3. Average optical efficiency and output power on 21 days per month

Date	Average optical efficiency	Average cosine efficiency	Average shading efficiency	Average truncation efficiency	Average output thermal power per unit area of mirror$\left(kW/m^2\right)$
1.21	80.90%	98.54%	92.32%	83.69%	1.179217062
2.21	79.73%	98.29%	91.22%	82.49%	1.179808225
3.21	79.16%	98.18%	90.67%	81.90%	1.180402654
4.21	78.98%	98.19%	90.45%	81.71%	1.181007605
5.21	79.86%	98.35%	91.31%	82.62%	1.181618159
6.21	81.52%	98.62%	92.96%	84.34%	1.182233134
7.21	82.98%	98.93%	94.32%	85.85%	1.182858917
8.21	85.61%	99.21%	97.04%	88.57%	1.183491717
9.21	87.38%	99.36%	98.34%	90.41%	1.184128349
10.21	86.87%	99.34%	96.34%	89.88%	1.184776122
11.21	85.20%	99.14%	96.64%	88.14%	1.185228288
12.21	82.62%	98.85%	93.99%	85.48%	1.179217062

Table.4. Annual average optical efficiency and output power meter

Average annual optical efficiency	Average annual cosine efficiency	Annual average shadow occlusion efficiency	Average annual truncation efficiency	Annual average output heat power $\left(MW\right)$	Mean annual mirror output thermal power per unit area $\left(kW/m^2\right)$
80.42%	98.75%	94.01%	99.73%	63.79	1.182

Table.5. Annual average optical efficiency and output power meter

Absorption tower position coordinates	Heliostat size (width × height)	Heliostat mounting height (m)	Total number of heliostats	Total heliostat area $\left(m^2\right)$
(0,0)	5.36×4.29	4.054	2186	50265.758

3. Conclusion

This paper focuses on the optimization design of heliostat field, adopts quadtree model and annealing model to design the optimal mirror field parameters, and further improves the annual average output thermal power per unit mirror area. The results show that through the combination of quadtree model and annealing model, not only the design parameters of the mirror field are optimized, but also the optical efficiency and thermal power output efficiency of the mirror field are significantly improved. This shows that the design and adjustment of heliostat field by using advanced optimization model can effectively improve the overall performance of solar thermal power system. In conclusion, this study successfully proves the effectiveness of using quadtree model and annealing model in heliostat field design. The application of these models not only optimizes the layout of the mirror field, but also improves the thermal efficiency of the system, which provides a valuable reference and guidance for the design of the heliostat field in the future. Future studies can further explore the application of other optimization models to continuously improve the efficiency and feasibility of solar thermal power generation technology.

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