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# A computational method for optimal design of the multi-tower heliostat field considering heliostats interactions

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A B S T R A C T

In multi-tower heliostat fields, although heliostats are capable of aiming at different receivers during the day, due to different orientations, neighboring heliostats might affect shading and blocking efficiency of each other reciprocally. In the proposed method of this paper, considering the mentioned effects and based on a group decision-making approach, each heliostat chooses the best receiver thus ensuring the highest possible instantaneous efficiency of the field. As a case study, this method is applied for the optimal design of a multi-tower field. Then, the field performance is simulated in a case where heliostats make decisions individually without considering the interactions. Finally, these results are compared with separated single tower fields' energy performance. Results of the case study show that, due to the high dependency on shading and blocking factor, the annual efficiency of the multi-tower field without considering the interactions is only slightly higher than the two separated single tower fields. However, using the proposed method, the optical performance of the multi-tower field improves and the annual efficiency of 54.58% is reachable, which is 0.21% higher than the case without considering the interactions and 0.26% higher than the separated single tower fields.



## 1. Introduction

CSP (Concentrating Solar Power) systems are one of the most promising renewable energy technologies which have grown rapidly in recent years. There are four main CSP technologies: parabolic trough, solar tower (central receiver system), linear Fresnel and dish Stirling [1]. Among these technologies, CRS (Central Receiver Systems) have distinctive merits in comparison with other CSP systems. In these systems, energy production in large scale, as well as higher temperature levels, due to the second thermodynamic law, results in higher energy efficiencies. Outlook for improvements of CRS is very significant in comparison with other CSP technologies [1]. Nevertheless, the cost of energy production in CRS systems is still higher than conventional fossil power systems and more efforts needed to make CRS systems more competitive in energy markets.

A CRS power plant comprises three main components: heliostat field, receiver and power block. A heliostat field consists of an array of tracking mirrors called heliostats which are spaced in a field in order to reflect solar incident onto a component called receiver [2]. A receiver absorbs concentrated radiation and converts it to the internal energy of a HTF (heat transfer fluid). The High-temperature fluid can be utilized in a power conversion block to produce electricity or other thermal applications.

Among these three subsystems, approximately 40% of total energy losses and half of the investment cost is attributed to the heliostat field [3]. Therefore, proposing innovative configurations for the heliostat field and designing them accurately and optimally is necessary for reduction of the cost of energy.

Energy losses in a heliostat field are caused by five main factors: Cosine loss, interception of the reflected rays also called spillage loss, shading and blocking between adjacent heliostats, attenuation of atmosphere and reflectivity of the heliostats mirrors. In order to minimize these energy losses, heliostats should be arranged properly. Therefore, an efficient procedure is required to design an optimal heliostat layout. These methods should be accurate and computationally efficient. Such codes for modeling of heliostat fields are described in Ref. [4]. Some of these codes such as HFLCAL [5], MIRVAL [6] and DELSOL [7] were proposed and implemented in many studies.

Some new studies have focused on developing methods for more accurate and faster calculation of heliostat fields' efficiency.

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**Nomenclature**

| | |
|---|---|
| $a$, $b$ | shape parameters of spiral pattern |
| $c_1$, $c_2$ | acceleration constants |
| $D$ | distance between heliostat and receiver, m |
| $D_R$ | diameter of the receiver, m |
| $D_{sep}$ | tower separation distance, m |
| $f$ | the focal point distance of the heliostat, m |
| $H_R$ | height of the receiver, m |
| $h_s$ | hour angle, degree |
| $h_{sr}$ | hour angle, rad |
| $h_{ss}$ | sunset hour angle, rad |
| $H_t$ | image dimension in the tangential plane at a distance $D$ from the mirror |
| $H_T$ | height of the tower, m |
| $i$ | index of particles number in PSO |
| $I_b$ | beam normal insolation, W/m$^2$ |
| $I_{ex}$ | extraterrestrial solar irradiance, W/m$^2$ |
| $I_o$ | the solar constant value 1353 W/m$^2$ |
| $j$ | iteration index in PSO algorithm |
| $k$ | iteration index in the proposed algorithm |
| $l$ | index of heliostats number |
| $L$ | latitude, rad |
| $L_H$ | length of the heliostat, m |
| $M$ | the set of information of those heliostats for evaluation in the current iteration |
| $M_{tot}$ | set of information of all heliostats in the field |
| $n$ | day number of the year |
| $\overrightarrow{n}$ | the unit vector of the heliostat surface |
| $N$ | set of information of those heliostats for re-evaluation in the next iteration |
| $r_1$, $r_2$, $r_3$ | random numbers between 0 and 1 |
| $r_l$ | polar radius of the lth element of the spiral pattern, m |
| $\overrightarrow{S}$ | the unit vector from the center of the heliostat toward the sun |
| $ST$ | solar time |
| $\overrightarrow{t}$ | the unit vector from the center of the heliostat toward the receiver |
| $t$ | calculation time step |
| $T_a$ | the optical transmittance of aerosols |
| $T_{mg}$ | the optical transmittance due to mixed gasses absorption |
| $T_o$ | the optical transmittance due to ozone absorption |
| $T_r$ | the optical transmittance of molecules |
| $T_w$ | the optical transmittance due to water vapor absorption |
| $v_i^j$ | the velocity of particle $i$ at iteration $j$ |
| $w$ | the inertia weight |
| $W_H$ | width of the heliostat, m |
| $W_s$ | image dimension in the sagittal plane at a distance $D$ from the mirror |
| $x_b$ | the position bound |
| $x_{g,best}^j$ | best-found position of all particles up to iteration $j$ |
| $x_i^j$ | the position of particle $i$ at iteration $j$ |
| $x_{i,best}^j$ | best-found position of particle $i$ up to iteration $j$ |
| $x_{randp}^j$ | the position of random particle |

*Greek symbols*

| | |
|---|---|
| $\alpha$ | solar altitude angle, rad |
| $a_s$ | solar azimuth angle, rad |
| $\delta_s$ | solar declination angle, degree |
| $\eta_{s\&b}$ | shading and blocking efficiency |
| $\eta_\rho$ | effective reflectivity |
| $\eta_{att}$ | attenuation efficiency |
| $\eta_{int}$ | interception efficiency |
| $\eta_{HF}$ | the instantaneous efficiency of heliostat field |
| $\eta_{cos}$ | cosine efficiency |
| $\eta_{annual}$ | the annual efficiency of heliostat field |
| $\theta_l$ | polar angle of the lth element of the spiral pattern, rad |
| $\sigma_t$ | standard deviation of tracking error, mrad |
| $\sigma_{tot}$ | the total standard deviation, mrad |
| $\sigma_{bq}$ | standard deviation of mirror slope errors, mrad |
| $\sigma_{sun}$ | standard deviation of sun shape, mrad |
| $\sigma_{ast}$ | standard deviation of astigmatic effect, mrad |
| $\sigma_s$ | standard deviation surface error, mrad |
| $\varphi$ | golden ratio $1+\sqrt{5}/2$ |
| $\omega$ | the angle between the sun rays and the heliostat normal |

Focusing on shadowing and blocking effect evaluation, Collado and Guallar [8] developed a code named Campo which can perform fast and accurate calculations of the shading and blocking efficiency by dividing the field into sectors. Besarati and Goswami [9] introduced a computationally efficient method for identifying potential shading and blocking heliostats based on a graphical approach. They validated their results with a redesigned spiral layout for PS10 plant by Noone et al. [10] with good agreement.

Some other studies have proposed new layouts for central receiver systems. Noone et al. [10] introduced a new layout for heliostat positions called spiral layout imitated from phyllotaxis arrangement found in nature. They showed that the spiral pattern performs better than radially staggered layouts and would result in both efficiency improvement and land area reduction. Danielli et al. [11] presented a new concept called the CMT (Concatenated Micro-Tower). In this configuration, by dynamic receiver allocation mounted on tower arrays, cosine efficiency increases thus optical efficiency can improve.

While energy efficiency of the heliostat field in a single tower configuration has been evaluated fast and accurate by many studies, there is still so much to study on multi-tower fields. Schramek and Mills [12] proposed a MTSA (Multi-Tower Solar Array) for urban areas. In their model, interception and attenuation losses were not included since in MTSA configuration, towers and heliostats are small (<10 m, <5 m$^2$) and these losses can be neglected. However, in larger multi-tower fields, where distances between heliostats and towers increase, interception and attenuation factor should be taken into account. In the study by Danielli et al., shading and blocking factor, as well as spillage factor, were not calculated while these factors have a considerable effect on the field efficiency. Likewise, in an article by Augsburger and Favrat [13], in which thermo-economic of multi-tower fields was investigated, and in a patent by Caldwell [14], shading and blocking factor were not considered in the modeling of the multi-tower field. Augsburger and Favrat preferred to use no-blocking layout introduced by Siala et al. [15]. However, shading factor was not considered and their models were limited to only no-blocking layouts. Furthermore, distances between heliostats in the no-blocking layouts are adjusted based on nearest towers, while for aiming at further receivers, the no-blocking condition may not be satisfied. Thus, without including shading and blocking factors, optimization processes in multi-tower fields would lead to