



Optical analysis of a multi-aperture solar central receiver system for high-temperature concentrating solar applications

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Abstract: A multi-aperture solar central receiver system is optically analyzed for increasing the net power to the receiver in a wide temperature range of 600–1800 K. A model system comprises a tower, a multi-aperture receiver with compound parabolic concentrators, and heliostat sub-fields. Optical modeling is performed using in-house developed Monte-Carlo ray-tracing programs. The heliostat sub-field geometrical configuration, the number of receiver apertures and optical properties of reflective surfaces are varied in the parametric study. Increasing the number of apertures from one to four increases the maximum net receiver power from 116 MW to 332 MW. The use of more than four apertures results in only limited further gain of the net receiver power but significantly decreases the overall optical efficiency and the solar-to-thermal efficiency. The optimal temperature for the maximized annual solar-to-exergy efficiency is found in the range of 1100–1200 K. This optimal temperature decreases slightly with an increasing number of apertures.

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1. Introduction

High temperatures (>1000 K) have been pursued for both solar thermochemical and concentrating solar power (CSP) applications. In solar thermochemical applications, high temperatures are required by the reduction and oxidation reaction steps of metal oxides to realize solar energy storage or fuel production [1–4]. In CSP applications, high temperatures increase solar energy conversion efficiency because of higher power cycle efficiency [5]. High-temperature receivers bring in high receiver emission losses, necessitating high solar concentration ratios at the receiver aperture (>1000 suns) [6,7]. High concentration ratios could be achieved by the implementation of cavity receivers with relatively small apertures, point-focusing primary optical concentrators such as solar dishes and heliostat fields of central receiver systems (CRSs), and secondary optical concentrators [8–11]. The most widely discussed secondary optical concentrator is the compound parabolic concentrator (CPC) which further increases the solar concentration ratio ideally by a factor of $1/\sin\theta_{\text{CPC}}$ or $1/\sin^2\theta_{\text{CPC}}$ for a two-dimensional (2D) or three-dimensional (3D) CPC, respectively, where θ_{CPC} is the acceptance angle of the CPC [3,12–17].

Higher plant power is favorable for the techno-economic performance of solar-driven power systems [18,19]. Our previous work on solar polar-field CRSs revealed that the power output from the cost-optimized high-temperature CRSs was small primarily due to the high spillage losses arising from the great distances from the far-away heliostats to the receiver [17]. For high-temperature applications, the configuration of CRSs with a surround field and an external receiver is not applicable for increasing the power output due to the high radiative emission losses [6]. Higher power output from high-temperature CRSs can be in principle obtained by

(i) a multi-tower CRS created by duplicating a single-tower system that encompasses a tower, a single-aperture receiver, a CPC, and a polar field [20] or (ii) a multi-aperture CRS created by coupling multiple polar fields to a multi-aperture receiver on a single tower. Method (i) offers better optical performance since heliostats are located at optimal positions to towers. However, it requires an increased number of the expensive components—towers, bringing in high capital costs. For method (ii), the investment for the tower can be used by more than one polar fields, thus capital costs are significantly reduced. The study on multi-aperture CRSs is rare in the literature and still far from thorough. The concept of multi-aperture receivers was applied in the 50 MW Khi Solar One plant constructed in South Africa where no CPC is used [21]. Example studies on multi-aperture CRSs with CPCs include that Schmitz et al. compared the performance of systems in three different configurations: a polar field coupled to a single-aperture receiver, a surround field coupled to an external receiver, and six polar fields coupled to a six-aperture receiver [22]. The system with a multi-aperture receiver and three sub-fields was included in an optimization study of a heliostat field layout by Pitz-Paal et al. for high-temperature solar thermochemical processing [23].

This study presents an optical analysis of a multi-aperture, high-temperature solar CRS with CPCs for increasing net receiver power. Optical modeling is performed using in-house Monte-Carlo ray-tracing (MCRT) programs written in Fortran. We explore the effects of heliostat sub-field geometrical configuration, number of apertures and optical properties of reflective surfaces on system optical and energetic performance. Optical systems are studied for applications in a wide temperature range of 600–1800 K in 100 K increments. Optimization for the maximized annual solar-to-thermal efficiency is conducted at each investigated temperature and selected numbers of apertures of 1, 2, 4, 6, and 8.

2. Model system

Figure 1(a) shows an example four-aperture CRS and includes the investigated parameters of the number of apertures, N_a , and the angle between adjacent heliostat sub-fields, β . Figure 1(b) depicts one section of a multi-aperture CRS and includes the investigated geometrical parameters of tower height, h_t , CPC acceptance angle, θ_{CPC} , and CPC entry aperture radius, r_{CPC} . Each aperture is coupled to a heliostat sub-field and a non-truncated three-dimensional (3D) CPC. We assume that the CPCs are of the same geometry and orientation characterized by a tilt angle, α_{CPC} , indicating that the shape of heliostat sub-fields before the trimming of low-efficiency heliostats are the same. CPC geometry is determined by the acceptance angle, θ_{CPC} , and the entry aperture radius, r_{CPC} . Table 1 includes details of the modeled CRSs and model assumptions. The shading effects by the tower, receiver and CPCs depend on their specific designs, i.e. size and shape, identification of which is beyond the scope of the present study.

The following two steps are taken for determining the boundary of the heliostat field: (i) We remove the heliostats whose centers are located outside the conic sections created by the intersection of CPC acceptance cones and a horizontal plane containing all heliostat centers [17,22]. The rays reflected by these heliostats are rejected by CPCs due to the CPC backward reflection [12]; (ii) We remove the heliostats with the instantaneous (at autumn equinox noon) overall optical efficiency (defined in Section 3.) lower than a defined threshold η_{tr} . The size of the target aperture, i.e. CPC entry aperture, is calculated for each trimmed sub-field to capture a defined ratio f_a of the reflected Gaussian-distributed radiation from the furthestmost heliostat to the tower. This method is adapted from [22] and was also used in our previous studies [17,27].

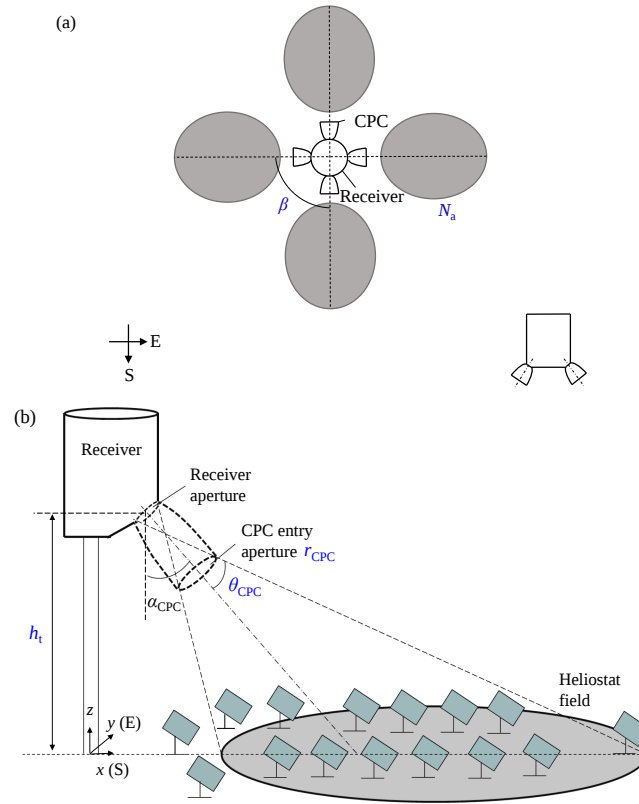


Fig. 1. Schematics of multi-aperture solar central receiver systems (CRSs): (a) an example CRS comprising a four-aperture receiver, four CPCs and four heliostat sub-fields, and (b) one section of a multi-aperture CRS, adapted from [17]. The investigated geometrical parameters are shown in blue, including number of apertures, N_a , angle between adjacent heliostat sub-fields, β , tower height, h_t , CPC acceptance angle, θ_{CPC} , and CPC entry aperture radius, r_{CPC} .

Table 1. Assumptions made for the simulations.

Parameters	Value
Plant location	Alice Springs, Australia
Sun shape model	Buie, circumsolar ratio (CSR) = 0.02 [24]
Tracking	azimuth–elevation, no tracking error
Optical surface reflectance	specular, wavelength- and direction-independent
Slope error model of optical surfaces	Rayleigh distribution [25]
Heliostat geometry	square, paraboloidal, single-facet
Heliostat field layout pattern	Campo [26]
Distance from the first heliostat row to tower	80 m
Maximum distance from heliostat to tower	1500 m
Maximum number of heliostat field zones	3
Distance between centers of two adjacent heliostats	1.1×heliostat diagonal length
Shading effects of the tower, receiver and CPCs	neglected

3. Analysis

Optical simulations are performed using in-house developed MCRT programs [28]. The MCRT technique provides the most robust, accurate and comprehensive results for predicting the system optical and energetic performance [28]. The real-time clear sky irradiance is modeled using the method described in [29]. Annual performance of the heliostat field is evaluated using the method developed by Grigoriev et al. (2015) and by employing bicubic spline interpolation of results for discrete sun positions [30,31]. The MCRT program for modeling the CPC is verified by computing the transmission-angle curve of a CPC with an acceptance angle of 16° , and comparing the results with those taken from [12]. The verification results were presented in [15]. The MCRT program for simulating CRSs was previously verified by comparing its predictions with those obtained using other ray-tracing tools [17,32].

The geometry and dimension of the intersected conic sections are determined by tower height, h_t , CPC acceptance angle, θ_{CPC} and CPC tilt angle, α_{CPC} , which was discussed in our previous study [17]. Figure 2 shows the conic sections for example CRSs with multi-aperture receivers of selected numbers of apertures, $N_a = 1, 2, 4, 6, 8$. Conic sections of elliptic and hyperbolic shapes are exhibited in Fig. 2(a–e) and (f–j), respectively. Overlap occurs between adjacent conic sections. For heliostats in the overlapped region, their aiming points are selected as the center of the target aperture facing towards the heliostat, to reduce the size of sun images on the target aperture and thus reduce spillage loss. Hence, heliostats in the overlapped regions are evenly distributed into the two adjacent sub-fields by the dashed lines as in Fig. 2. Figure 2 demonstrates that the total intersecting land area of conic sections increases with an increasing N_a and a larger θ_{CPC} , indicating potentially higher power output. However, the concentration ratio boost of the 3D CPC, equal to $1/\sin^2\theta_{CPC}$, decreases with the increase of θ_{CPC} . As will be illustrated in Eq. (5), the receiver absorption efficiency is reduced as a result of lower concentration ratios at the receiver aperture. The tradeoffs between the increase in net receiver power and the decrease in field optical and receiver absorption efficiencies are addressed in this study.

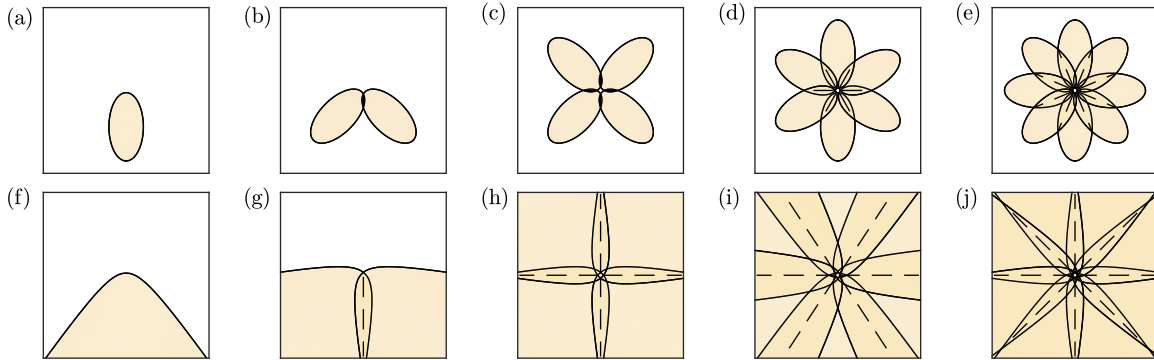


Fig. 2. Conic sections created by intersecting CPC acceptance cones with a horizontal plane containing all heliostat centers for an example CRS with a tower height h_t of 150 m, a CPC tilt angle α_{CPC} of 45° and a CPC acceptance angles θ_{CPC} of 35° and 55° for (a–e) and (f–j), respectively. Elliptic and hyperbolic conic sections are identified for cases (a–e) and (f–j), respectively. Figure (a, f), (b, g), (c, h), (d, i), and (e, j), respectively, show the layouts of CRSs with numbers of apertures, $N_a = 1, 2, 4, 6$, and 8 .

System performance is characterized by (i) instantaneous overall optical efficiency of a single heliostat or a heliostat field, $\eta_{h,opt}$ and $\eta_{tot,opt}$, respectively, and annual overall optical efficiency of a heliostat field, $\bar{\eta}_{tot,opt}$, (ii) net receiver power, $\dot{Q}_{tot,net}$, i.e. the total radiative power absorbed in the receiver at autumn equinox noon, (iii) average optical concentration ratio at the receiver aperture

at autumn equinox noon, C_{rec} , (iv) instantaneous and annual receiver absorption efficiency, η_{rec} and $\bar{\eta}_{\text{rec}}$, respectively, (v) instantaneous and annual solar-to-thermal efficiency, $\eta_{\text{s-t}}$ and $\bar{\eta}_{\text{s-t}}$, respectively, and (vi) annual solar-to-exergy efficiency, $\bar{\eta}_{\text{s-x}}$.

Overall optical efficiency. Instantaneous overall optical efficiency of a single heliostat and a heliostat field account for cosine, shading, surface absorption, blocking, atmospheric attenuation, and spillage losses [14]. For a heliostat field consisting of a number of sub-fields, $\eta_{\text{tot,opt}}$ is defined as the total radiative power intercepted by all receiver apertures to the maximum total radiative power $\dot{Q}_{\text{f,max}}$ collected when sun rays incident normally on an area equal to the total area of installed heliostats, $A_{\text{h,tot}} = n_{\text{h}}A_{\text{h}}$ (n_{h} is the total number of installed heliostats and A_{h} is the mirror area of a heliostat) [14,33].

$$\eta_{\text{h,opt}} = \eta_{\text{h,cos}}\eta_{\text{h,shade}}\eta_{\text{h,abs}}\eta_{\text{h,block}}\eta_{\text{h,aa}}\eta_{\text{h,int}} \quad (1)$$

$$\eta_{\text{tot,opt}} \equiv \frac{\dot{Q}_{\text{tot,rec}}}{\dot{Q}_{\text{f,max}}} = \frac{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{rec}}}{Gn_{\text{h}}A_{\text{h}}} = \eta_{\text{cos}}\eta_{\text{shade}}\eta_{\text{abs}}\eta_{\text{block}}\eta_{\text{aa}}\eta_{\text{int}} \quad (2)$$

where $\dot{Q}_{\text{tot,rec}}$ and $\dot{Q}_{i,\text{rec}}$ represent the total radiative power intercepted by all apertures and the i_{th} aperture, respectively, and G is the instantaneous clear-sky solar irradiance [17,29].

Annual overall optical efficiency of the field, $\bar{\eta}_{\text{tot,opt}}$, is defined as the ratio of the total radiative energy intercepted by all apertures to the maximum radiative energy incident on all heliostats in a year [33].

$$\bar{\eta}_{\text{tot,opt}} = \frac{\sum_{i=1}^{N_{\text{a}}} \int_{\text{year}} \dot{Q}_{i,\text{rec}} dt}{n_{\text{h}}A_{\text{h}} \int_{\text{year}} G dt} \quad (3)$$

Receiver absorption efficiency. Net receiver power, $\dot{Q}_{\text{tot,net}}$, is equal to the sum of the radiative power absorbed through each aperture, $\dot{Q}_{i,\text{net}}$. $\dot{Q}_{i,\text{net}}$ is equal to the radiative power intercepted by an individual aperture, $\dot{Q}_{i,\text{rec}}$, multiplied by the instantaneous receiver absorption efficiency, $\eta_{i,\text{rec}}$.

$$\eta_{\text{tot,rec}} \equiv \frac{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{net}}}{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{rec}}} = \frac{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{rec}} \eta_{i,\text{rec}}}{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{rec}}} \quad (4)$$

We assume that the receiver is an iso-thermal, perfectly-insulated blackbody without reflective, conductive and convective heat losses [1,23,34]. The instantaneous absorption efficiency, $\eta_{i,\text{rec}}$, at each aperture of the simplified multi-aperture receiver at T_{rec} is calculated as

$$\eta_{i,\text{rec}} = 1 - \frac{\sigma T_{\text{rec}}^4}{G_0 C_{i,\text{rec}}} \quad (5)$$

where σ is the Stefan–Boltzmann constant, $\sigma = 5.67 \times 10^{-8} \text{ W m}^{-2} \text{ K}^{-4}$, and G_0 is a reference solar irradiance taken as 1000 W m^{-2} for the definition of the average optical concentration ratio at the receiver aperture, $C_{i,\text{rec}}$.

The annual absorption efficiency of the multi-aperture receiver, $\bar{\eta}_{\text{tot,rec}}$, is calculated as:

$$\bar{\eta}_{\text{tot,rec}} = \frac{\sum_{i=1}^{N_{\text{a}}} \int_{\text{year}} \dot{Q}_{i,\text{net}} dt}{\sum_{i=1}^{N_{\text{a}}} \int_{\text{year}} \dot{Q}_{i,\text{rec}} dt} \quad (6)$$

Solar-to-thermal efficiency. Instantaneous solar-to-thermal efficiency, $\eta_{\text{s-t}}$, is defined as the ratio of the total radiative power absorbed by the multi-aperture receiver, $\dot{Q}_{\text{tot,net}}$, to $\dot{Q}_{\text{f,max}}$.

$$\eta_{\text{s-t}} = \frac{\dot{Q}_{\text{tot,net}}}{\dot{Q}_{\text{f,max}}} = \frac{\sum_{i=1}^{N_{\text{a}}} \dot{Q}_{i,\text{net}}}{Gn_{\text{h}}A_{\text{h}}} \quad (7)$$

Annual solar-to-thermal efficiency, $\bar{\eta}_{s-t}$, is defined as the ratio of the total radiative energy absorbed in the receiver to $\dot{Q}_{f,max}$ integrated for a year,

$$\bar{\eta}_{s-t} = \bar{\eta}_{tot,opt} \bar{\eta}_{tot,rec} = \frac{\sum_{i=1}^{N_a} \int_{year} \dot{Q}_{i,net} dt}{n_h A_h \int_{year} G dt} \quad (8)$$

The solar-to-thermal efficiency measures the performance of the overall optical system including the heliostat field consisting of multiple sub-fields, the CPCs and the multi-aperture receiver.

Solar-to-exergy efficiency. Annual solar-to-exergy efficiency, $\bar{\eta}_{s-x}$, is defined as the ratio of the system annual exergy output to $\dot{Q}_{f,max}$ integrated for a year. $\bar{\eta}_{s-x}$ is equal to the annual solar-to-thermal efficiency multiplied by the Carnot efficiency.

$$\bar{\eta}_{s-x} = \bar{\eta}_{s-t} \eta_{Carnot} = \bar{\eta}_{s-t} \left(1 - \frac{T_0}{T_{rec}} \right) \quad (9)$$

where T_0 is the temperature of the cold reservoir of a power cycle and is taken as the ambient temperature of 293 K. The solar-to-exergy efficiency measures the upper limit of the solar-to-electric efficiency for a solar power plant, as well as the maximum solar-to-fuel efficiency for an ideal cyclic process for a solar thermochemical plant [1,17]. High-temperature receivers increase the thermal-to-electric or thermal-to-fuel conversion efficiency, thus leading to a higher solar-to-exergy efficiency.

In a practical plant, thermal expansion and degradation may occur to CPCs since the CPCs are exposed to high-flux irradiation and contaminants from the receiver cavity and the surroundings. High-flux irradiation to the CPCs results from the concentrated solar radiation by optical concentrators and the lost radiation through the high-temperature receiver apertures, namely the receiver radiative emission and reflective losses. The total optical error and reflectance of the heliostat surface are impacted by factors such as structural shape, mirror curvature, tracking error, as well as wind and contamination during operation. Hence, in this study we include the discussion of the effects of the slope error and reflectance of optical surfaces of heliostats and CPCs.

4. Results

Based on the described optical model and assumptions, the results of optical analysis on the multi-aperture CRS are calculated. In Subsections 4.1, 4.2 and 4.3, we present the investigation on the effects of the heliostat sub-field geometrical configuration, the number of apertures, and the optical properties of reflective surfaces, respectively, on system optical and energetic performance. Subsection 4.2 also includes the optimization results of CRSs at each studied receiver temperature and selected numbers of apertures of 1, 2, 4, 6, and 8. Table 2 lists the baseline parameter set.

4.1. Heliostat sub-field geometrical configuration

We use the angle between the axis of a polar field and the south direction, θ_f (positive: clockwise), to define the relative position of a polar field to the tower (see Fig. 3(a)). We quantitatively evaluate the performance of CRSs with a single-aperture receiver coupled to one polar field, i.e. $N_a = 1$, positioned at different directions around the tower. No trimming of low-efficiency heliostats, i.e. $\eta_{tr} = 0$, is applied for the parametric study conducted in this section. In Fig. 3(b), we exhibit the annual overall optical efficiency, $\bar{\eta}_{tot,opt}$, annual solar-to-thermal efficiency, $\bar{\eta}_{s-t}$ and net receiver power, $\dot{Q}_{tot,net}$ for CRSs with selected θ_f varying from 0° to 330° in 30° increments. According to Fig. 3, the system performance decreases as the field moves away from the south direction to the tower ($\theta_f = 0^\circ$). East-west symmetry can be seen in Fig. 3(b). The field with the

Table 2. Baseline parameter set of a solar central receiver system

Parameters	Value
Number of apertures, N_a	6
Tower height, h_t	250 m
Heliostat surface area, A_h	100 m ²
CPC acceptance angle, θ_{CPC}	30°
CPC entry aperture radius, r_{CPC}	5 m
CPC axis tilt angle, α_{CPC}	45°
Reflectance of heliostat and CPC surfaces, ρ_h and ρ_{CPC}	0.9 and 0.95
Slope error of heliostat and CPC surfaces, σ_h and σ_{CPC}	1.5 and 0.5 mrad
Optical efficiency trimming threshold, η_{tr}	0.6

worst performance is found at $\theta_f = 180^\circ$ and yields 9.3 MW (1.8%) lower $\dot{Q}_{net}$, 8.1% lower $\bar{\eta}_{opt}$, and 7.9% lower $\bar{\eta}_{s-t}$ than the optimal field with $\theta_f = 0^\circ$.

Cosine effect is the main reason for causing the performance difference between CRSs of different θ_f [35]. Cosine efficiency is determined by the relative position of the sun, the heliostat and the target aperture. Figure 4 exhibits the cosine efficiency map for three example sun positions at 6 am, 9 am and 12 pm on an autumn equinox day. For each sun position, significantly higher cosine efficiencies are observed for positions at the opposite side of the tower as the sun. The cosine efficiency for heliostats at the west/east to the tower is only higher when the sun is in the east/west direction at relatively lower solar irradiance. Hence, the CRS with heliostats arranged to the south of the tower offers the highest cosine efficiency, followed by the east/west and the north. For this reason, the heliostat field is typically arranged to the south or north of the tower for polar-field CRSs constructed in the southern or northern hemisphere, respectively.

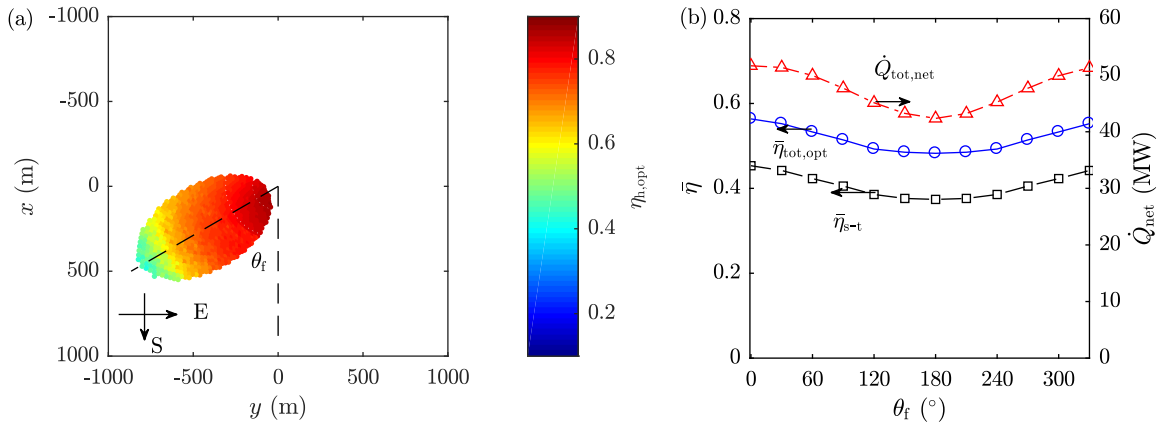


Fig. 3. Optical and energetic performance of polar-field central receiver systems (CRSs) characterized by (a) instantaneous (at autumn equinox noon) overall optical efficiency of each heliostat, $\eta_{h,opt}$, in an example CRS of $\theta_f = 60^\circ$ and (b) annual overall optical efficiency, $\bar{\eta}_{tot,opt}$, annual solar-to-thermal efficiency, $\bar{\eta}_{s-t}$, and net receiver power, $\dot{Q}_{net}$, for CRSs of selected θ_f varying from 0° to 330° in 30° increments and an assumed receiver temperature of 1600 K.

For CRSs with the same number of apertures, N_a , different angles between two adjacent sub-fields, β , can be applied, resulting in different heliostat sub-field geometrical configurations.

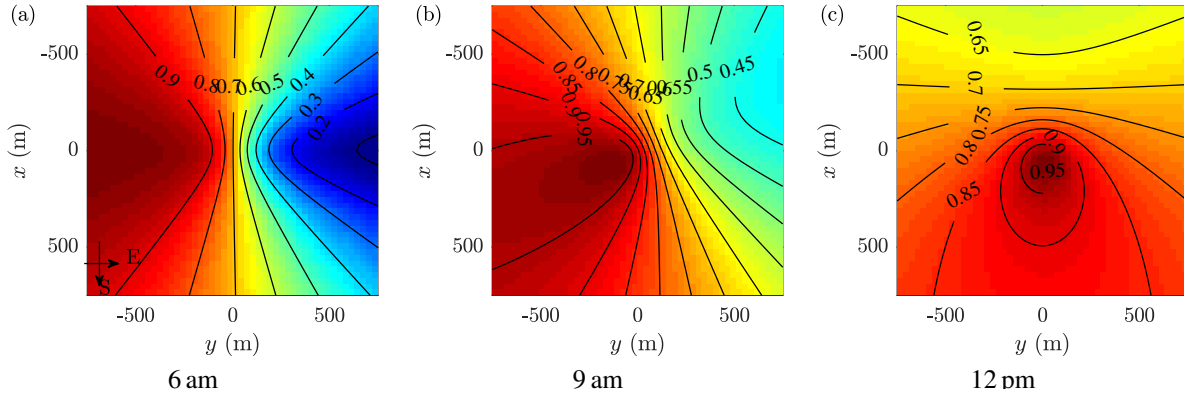


Fig. 4. Cosine efficiency maps for three example solar hours of the autumn equinox day: (a) 6 am, (b) 9 am and (c) 12 pm. The tower is located at the origin point.

Figure 5 shows heliostat field layouts of CRSs with selected N_a of 4, 6, 8, and β of 20° , 30° , 45° , 60° , 90° . The maximum possible β for CRSs with N_a of 4, 6, 8 are 90° , 60° , and 45° , respectively, where the sub-fields are evenly distributed in the field around the tower. The performance, characterized by the instantaneous overall optical efficiency $\eta_{\text{tot,opt}}$, instantaneous solar-to-thermal efficiency $\eta_{\text{s-t}}$, and $\dot{Q}_{\text{tot,net}}$, of each CRS in Fig. 5 is exhibited in Fig. 6. Results of Figs. 5 and 6 are obtained for CRSs with a same assumed receiver aperture radius of 2.5 m.

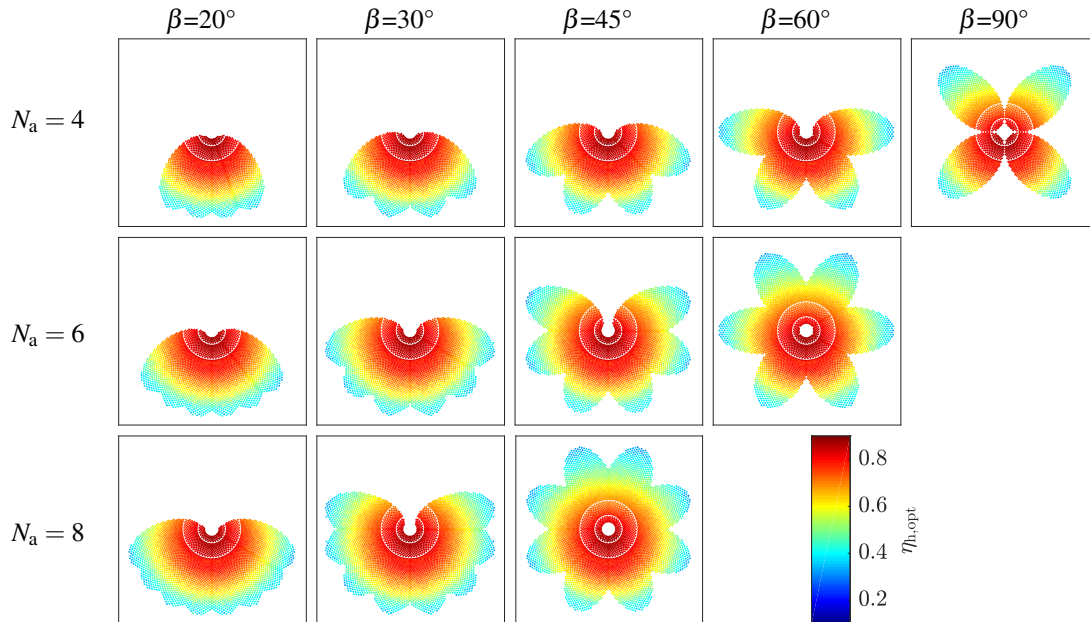


Fig. 5. Configurations of heliostat sub-fields for central receiver systems with selected numbers of apertures, $N_a = 4, 6, 8$, and angles between sub-fields, $\beta = 20^\circ, 30^\circ, 45^\circ, 60^\circ, 90^\circ$. The color scale indicates the instantaneous (at autumn equinox noon) overall optical efficiency of each heliostat, $\eta_{\text{h,opt}}$. Other parameters are taken as the parameter set in Table 2.

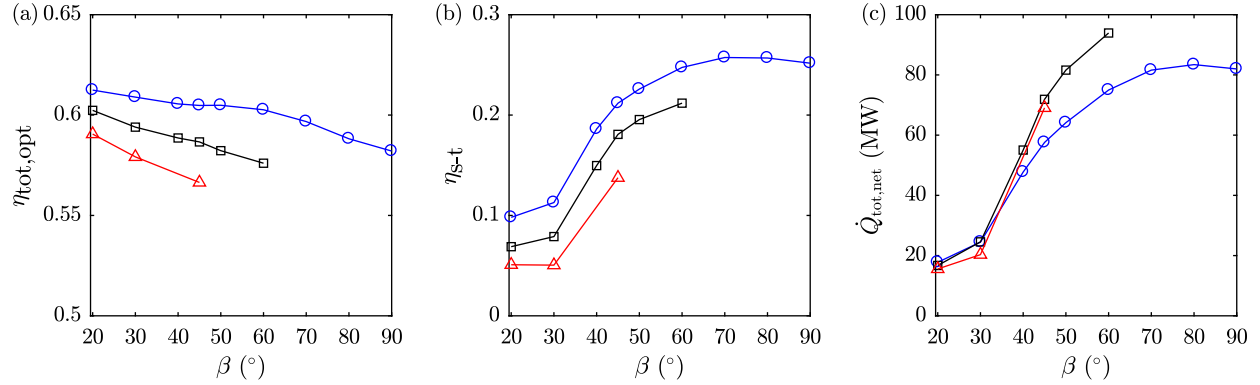


Fig. 6. Optical and energetic performance of the systems shown in Fig. 5, characterized by (a) instantaneous overall optical efficiency, $\eta_{\text{tot,opt}}$, (b) instantaneous solar-to-thermal efficiency, η_{s-t} , and (c) net receiver power, $\dot{Q}_{\text{tot,net}}$, for selected numbers of apertures, N_a of 4, 6 and 8, and sub-field angles β in the range of 20–90°. The receiver temperature is assumed as 1200 K.

According to Fig. 5, when the sub-field angle β is increased, the overlapping area decreases while more low-efficiency heliostats located away from the south are included. As a result, as revealed in Fig. 6, $\eta_{\text{tot,opt}}$ decreases and $\dot{Q}_{\text{tot,net}}$ increases for a larger β . CRSs with a larger β offer higher η_{s-t} , which is attributed to the increased concentration ratio at the receiver aperture due to an increasing total number of heliostats. In addition, the decrease in $\eta_{\text{tot,opt}}$ and η_{s-t} and the increase in $\dot{Q}_{\text{tot,net}}$ are observed for increasing N_a from four to six. However, the further increase of N_a from six to eight results in reduced $\dot{Q}_{\text{tot,net}}$ (see Fig. 6(c)), which reveals that the increased receiver emission loss caused by a larger total area of apertures outweighs the gain of intercepted radiation by employing more heliostats. For parametric optimization in Section 4.2, we select sub-field layouts with the maximum possible β for each N_a to achieve the maximized net receiver power and a larger space between sub-fields for the potential use of CPCs of larger acceptance angles. These results demonstrate the tradeoff between efficiencies and net receiver power for the selection of N_a and β .

For the maximum β , two geometrical configurations of heliostat sub-fields are possible. For example, Fig. 7 displays the two configurations of heliostat sub-fields in four-aperture, six-aperture and eight-aperture CRSs. By simulating the instantaneous performance, it is found that these two configurations offer similar performance. For example, for the baseline six-aperture systems with layouts 1 (Fig. 7(c)) and 2 (Fig. 7(d)), the instantaneous overall optical and solar-to-thermal efficiencies and net receiver power are 0.516 and 0.515, 0.283 and 0.279, and 125.5 MW and 122.3 MW, respectively, for an assumed receiver temperature of 1200 K.

4.2. Number of apertures

Based on the optical analysis performed with the baseline parameters, we conduct preliminarily parametric optimization of CRSs with parameters listed in Table 3. Other parameters not included in Table 3 are taken from the baseline parameter set as in Table 2. Annual simulations are performed for all CRS configurations. For the optical simulations in this section, the maximum possible sub-field angle β of 90°, 60° and 45° are employed for N_a of 4, 6 and 8, respectively. For $N_a = 1$, the field is placed to the south of the tower. For $N_a = 2$, β is selected as 90° and the two sub-fields are positioned to the south of the tower, as can be seen in Fig. 2.

The parameters of the optimized CRSs of $N_a = 4, 6, 8$ for the maximized $\bar{\eta}_{s-t}$ are found to be: $h_t = 250$ m, $\theta_{\text{CPC}} = 30^\circ$, $\eta_{\text{tr}} = 0.6$, and $f_a = 0.9$. Figure 8 shows the geometrical configurations

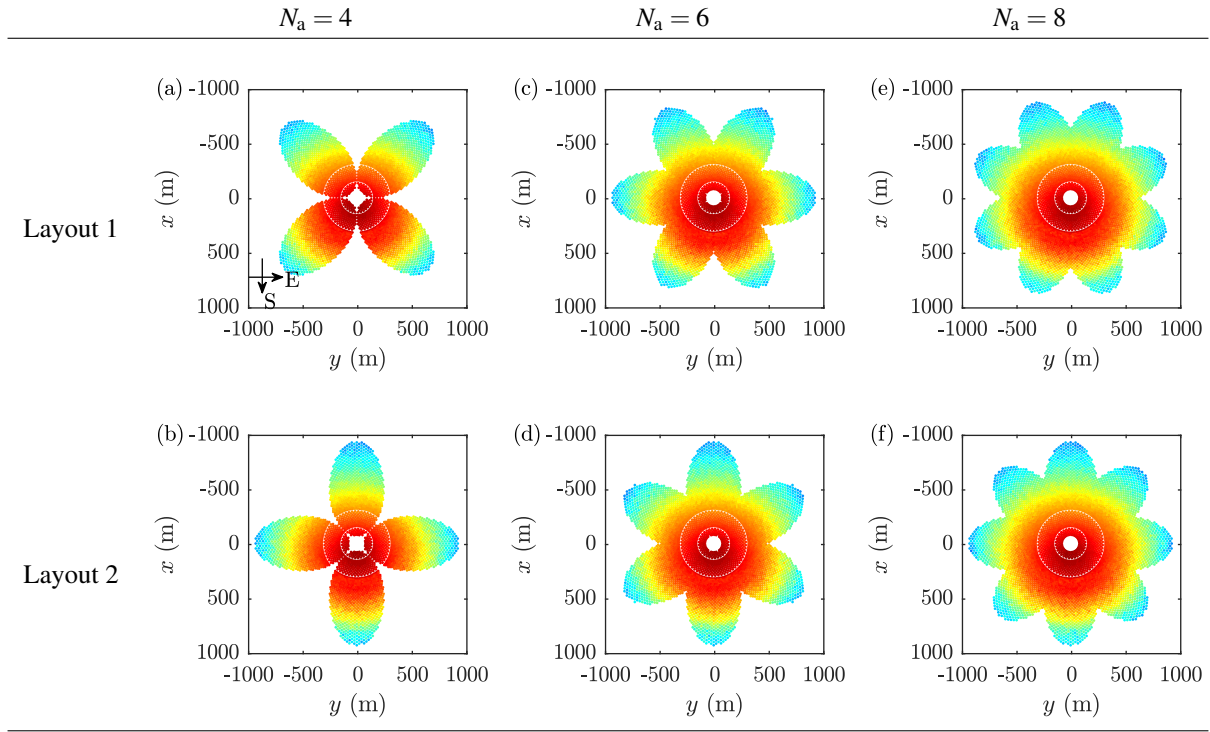


Fig. 7. Two configurations of heliostat sub-fields for systems with selected numbers of apertures, $N_a = 4, 6, 8$: Layout 1 and 2. The color scale indicates the instantaneous (at autumn equinox noon) overall optical efficiency of each heliostat, $\eta_{h,opt}$, using the same legend as that of Fig. 5.

of heliostat sub-fields of these optimized CRSs. Figure 9 shows the Pareto front of $\bar{\eta}_{s-t}$ and $\dot{Q}_{tot,net}$ calculated for all simulated CRSs with selected N_a of 1, 2, 4, 6, 8 and T_{rec} of 800 K, 1200 K and 1600 K. To determine the Pareto front, $\dot{Q}_{tot,net}$ is uniformly discretized and the Pareto front is selected as the cases leading to the maximum $\bar{\eta}_{s-t}$ among all cases within each discretized interval of $\dot{Q}_{tot,net}$. Figure 10 shows the maximum annual solar-to-thermal efficiency, $\bar{\eta}_{s-t,max}$, and the maximum annual solar-to-exergy efficiency, $\bar{\eta}_{s-x,max}$, for CRSs with selected $N_a = 1, 2, 4, 6, 8$ and T_{rec} varying from 600 K to 1800 K in 100 K increments. Based on Figs. 8, 9 and 10, it is found that:

- The maximum achievable $\dot{Q}_{tot,net}$ increases dramatically for N_a increased from 1 to 4. However, no significant improvement of $\dot{Q}_{tot,net}$ is found by further increasing N_a over 4.
- The maximum $\bar{\eta}_{s-t}$ decreases with an increasing N_a , due to higher inherent optical losses resulting from using more CPCs and higher receiver emission losses due to a larger total area of apertures.
- According to Fig. 9(c), for CRSs with $T_{rec} = 1600$ K and $N_a = 4, 6, 8$, the maximum $\bar{\eta}_{s-t}$ of approximately 0.44, 0.438, 0.42, respectively, are obtained where $\dot{Q}_{net}$ is approximately 150 MW.
- According to Fig. 9, CRSs with $N_a = 4$ and 6 offer close performance, while CRSs with $N_a = 8$ yield lower $\bar{\eta}_{s-t}$. The difference of $\bar{\eta}_{s-t}$ between CRSs with $N_a = 6$ and 8 increases for a higher T_{rec} .

- $\bar{\eta}_{s-t}$ and $\dot{Q}_{tot,net}$ decrease as T_{rec} increases as a result of higher receiver emission losses. The benefits of high-temperature receivers are manifested in higher annual solar-to-exergy efficiency, $\bar{\eta}_{s-x}$ (see Fig. 10(b)), the maximum values of which peak at T_{rec} of about 1100–1200 K depending on the implemented N_a .
- According to Fig. 10(b), the optimum temperatures for the maximized $\bar{\eta}_{s-x}$ differ for selected N_a and slightly decrease with an increasing N_a .

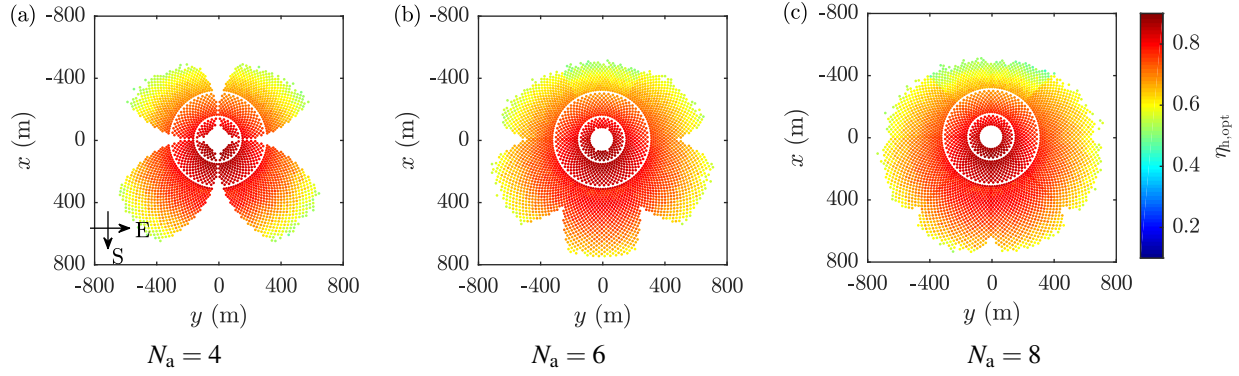


Fig. 8. Heliostat field layouts of the optimized solar central receiver systems with selected numbers of apertures N_a of (a) 4, (b) 6, and (c) 8. The color scale indicates the instantaneous (at autumn equinox noon) overall optical efficiency of each heliostat, $\eta_{h,opt}$.

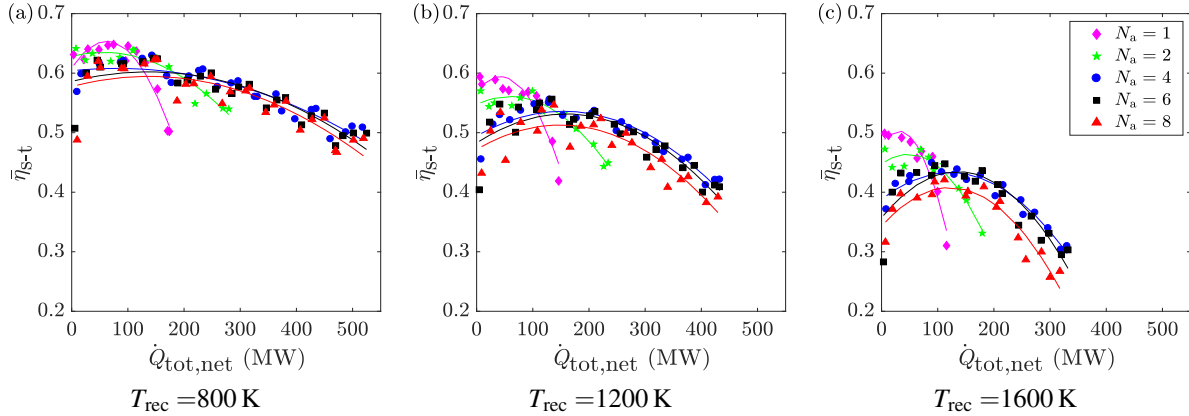


Fig. 9. The Pareto front of annual solar-to-thermal efficiency $\bar{\eta}_{s-t}$ and net receiver power $\dot{Q}_{tot,net}$ for all simulated systems with selected numbers of apertures, N_a of 1, 2, 4, 6, 8, and selected receiver temperatures T_{rec} of (a) 800 K, (b) 1200 K and (c) 1600 K.

4.3. Optical properties of reflective surfaces

We investigate changes in system performance resulting from varying optical properties including the reflectance and the slope error of heliostat and CPC surfaces. Figure 11 shows $\bar{\eta}_{s-t}$ and $\dot{Q}_{tot,net}$ as functions of the reflectance and slope error of heliostat and CPC surfaces, varying from 0.7 to 0.95 in 0.05 increments and 0.5 mrad to 5.5 mrad in 1 mrad increments, respectively. The baseline parameter set in Table 2 is taken for the calculations in this section.

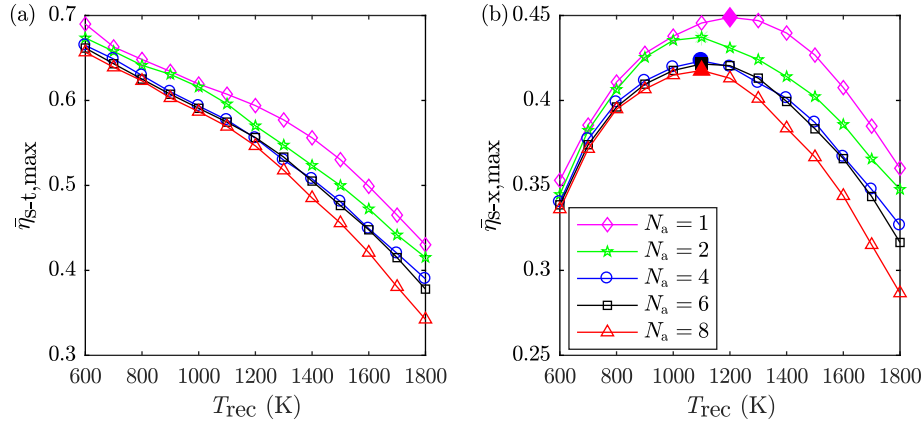


Fig. 10. The maximum (a) annual solar-to-thermal efficiency, $\bar{\eta}_{s-t,max}$, and (b) annual solar-to-exergy efficiency, $\bar{\eta}_{s-x,max}$, of systems with selected numbers of apertures, N_a of 1, 2, 4, 6, 8, and receiver temperatures T_{rec} varying from 600 K to 1800 K in 100 K increments.

Table 3. Parameters simulated in the optimization

Parameters	Values
Number of apertures, N_a	1, 2, 4, 6, 8
Tower height, h_t	90, 130, 170, 210, 250 m
CPC acceptance angle, θ_{CPC}	30°, 40°, 50°, 60°, 70°
Optical efficiency trimming threshold, η_{tr}	0.2, 0.3, 0.4, 0.5, 0.6, 0.7
Parameters determining CPC entry aperture radius, f_a	0.7, 0.8, 0.9, 0.95, 0.99

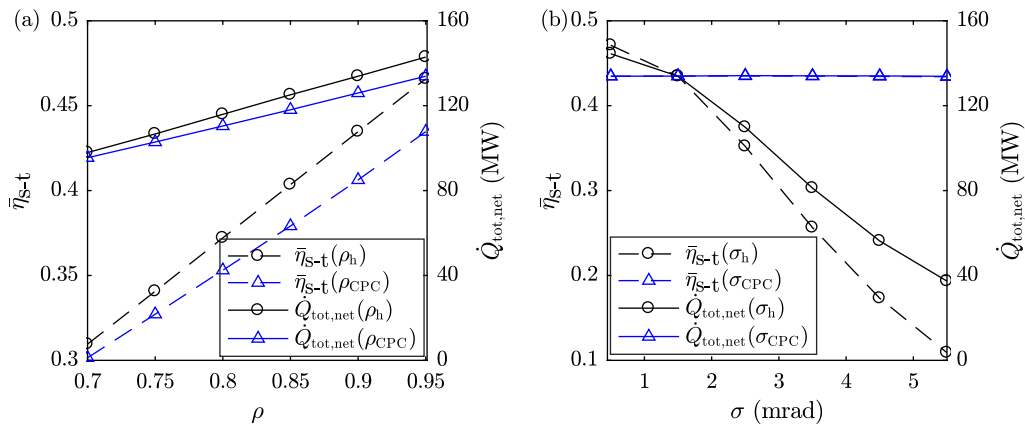


Fig. 11. Effects of heliostat and CPC surface (a) reflectance, ρ_h and ρ_{CPC} , and (b) slope error, σ_h and σ_{CPC} , on annual solar-to-thermal efficiency, $\bar{\eta}_{s-t}$, and net receiver power, $\dot{Q}_{tot,net}$, for the baseline system with parameters as in Table 2.

Based on Fig. 11(a), with the increase of heliostat surface reflectance from 0.7 to 0.95, $\bar{\eta}_{s-t}$ and $\dot{Q}_{tot,net}$ increase from 0.31 to 0.435 (31.8%) and 97.9 MW to 133.9 MW (36.8%), respectively. The system energetic performance is slightly more sensitive to the reflectance of the heliostat surface, ρ_h , than the reflectance of the CPC surface, ρ_{CPC} . According to Fig. 11(b), the increase of heliostat surface slope error σ_h from 0.5 mrad to 5.5 mrad leads to a significant drop of $\dot{Q}_{tot,net}$ and $\bar{\eta}_{s-t}$ from 144.5 MW to 37.3 MW (74.2%) and 0.47 to 0.11 (76.6%), respectively. It is worthwhile to note that the CPC surface slope error σ_{CPC} is found to have a minor effect on the system performance. This is due to a significantly larger optical length from heliostats to the CPC exit aperture than the optical length from the CPC reflective surface to the CPC exit aperture. Considering the short optical length from the CPC reflective surface to the CPC exit aperture, the reflected rays are primarily intercepted by the receiver despite a larger slope error. Based on these results, the reflectance of the CPC optical surface is more important than the slope error and should be paid more attention to in the manufacturing process.

5. Summary and conclusions

Optics of a solar central receiver system with a multi-aperture receiver coupled to multiple heliostat sub-fields and compound parabolic concentrators has been studied. Optical simulations were performed using in-house Monte-Carlo ray-tracing programs. We explored the effects of the heliostat sub-field geometrical configuration, the number of apertures and the optical properties of reflective surfaces on the optical and energetic performance of systems with the receiver temperature in the range of 600–1800 K. The system characteristics including the maximum net receiver power, instantaneous and annual overall optical, solar-to-thermal and solar-to-exergy efficiencies were analyzed.

Under the assumptions made in this study, it is found that despite reduced optical and solar-to-thermal efficiencies, the maximum net receiver power is significantly increased via the design of the multi-aperture receiver and multiple heliostat sub-fields. Cosine effect is the main reason for the decreased optical efficiency. We compared two types of sub-field geometrical configurations for systems with the same number of apertures and found that they offer close system performance. From parametric optimization, we demonstrated that the net receiver power is significantly boosted by increasing the number of apertures from one to four, while further increasing the number of apertures over four leads to only limited gain of net receiver power but greatly reduced efficiencies. Optimal receiver temperature for the maximized annual solar-to-exergy efficiency is found in the range of 1100–1200 K and this optimal temperature decreases with an increasing number of apertures. Comparison study on the optical properties of the heliostat and CPC surfaces revealed that the CPC slope error has a minor effect on the system performance. The present optical study enlightens the design of the entire multi-aperture solar central receiver systems in the future.

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Disclosures

The authors declare no conflicts of interest.

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