Design optimization of ultra-high concentrator photovoltaic system using two-stage non-imaging solar concentrator

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Abstract. This paper presents a systematic approach for optimizing the design of ultra-high concentrator photovoltaic (UHCPV) system comprised of non-imaging dish concentrator (primary optical element) and crossed compound parabolic concentrator (secondary optical element). The optimization process includes the design of primary and secondary optics by considering the focal distance, spillage losses and rim angle of the dish concentrator. The imperfection factors, i.e. mirror reflectivity of 93%, lens' optical efficiency of 85%, circumsolar ratio of 0.2 and mirror surface slope error of 2 mrad, were considered in the simulation to avoid the overestimation of output power. The proposed UHCPV system is capable of attaining effective ultra-high solar concentration ratio of 1475 suns and DC system efficiency of 31.8%.

1. Introduction

Solar concentrator is important in the development of ultra-high concentrator photovoltaic (UHCPV) power generation system that transforms highly focused solar energy into electrical energy. In the UHCPV system, a solar concentrator that is made of relatively inexpensive optics (mirrors or lenses), has been deployed to concentrate the sunlight onto a receiver that is fitted out with multi-junction solar cells (MJSCs) at ultra-high solar concentration ratio (SCR) (> 1000 suns). This approach is capable of cutting down the use of expensive semiconductor materials. The higher the concentration ratio, the lower the levelized cost of electricity (LCOE) [1-3]. Therefore, the motivation behind developing solar concentrator for the UHCPV system is to further reduce the cost of solar electricity, whereby this system is more competitive than other renewable technologies.

To further reduce the cost of UHCPV system, the optimal optical design of solar concentrator is necessary so that maximum solar energy can be harnessed from the MJSCs. Several researchers have proposed several types of solar concentrators to attain ultra-high SCR and reasonably good optical performance [4-6]. For example, Perez-Higuera et al have proposed a two-optical-unit system comprised of two Fresnel lenses, two planar mirrors and a MJSC [7]. The geometrical concentration ratio of the proposed two-optical-unit system is 952 suns. However, the system efficiency is only 17.2% owing to poor optical performance and non-uniform illumination distributed on the MJSC. Besides, Ferrer-Rodriguez et al have introduced a 4-off-axis-unit Cassegrain-based concentrator to achieve effective concentration ratio of 1682 suns [8]. The presented concentrator consists of four paraboloid mirrors, four hyperboloid mirrors, a glass cover, a homogenizer and a MJSC. The optical
efficiency of the three-stage optical system is limited to 73% due to shadowing, reflection and transmission losses in the system. Based on the above-mentioned systems, the performance of a UHCPV system is restricted by the optical design of solar concentrator and the non-uniform solar illumination distributed on the MJSCs.

In this study, a two-stage non-imaging solar concentrator that is capable of producing ultra-high SCR and reasonably uniform solar illumination focused on the MJSCs has been proposed. Instead of using the typical solar concentrators (Fresnel lens or parabolic dish), which are facing great challenge to produce uniform illumination, the primary optical element (POE), i.e. non-imaging dish concentrator (NIDC), comprises multi-faceted mirrors. Despite the employment of flat facet mirrors in the NIDC, the resultant flux distribution from simple super-positioning of all the reflected sunlight is inevitably non-uniform near the peripheral area. Therefore, a secondary optical element (SOE) is required for homogenizing the reflected sunlight from NIDC. Besides acts as a homogenizer, an array of crossed compound parabolic concentrator (CCPC) lenses, which are the SOEs, have been introduced to further focus the concentrated sunlight by the POE onto an array of MJSCs. This approach can reduce the use of expensive semiconductor materials. This new design maximizes the absorption of concentrated sunlight and further reduces the cost of UHCPV power generation system.

2. Overview of the UHCPV system

Figure 1. 3-D view of the proposed UHCPV system. (a) POE, non-imaging dish concentrator (NIDC); (b) SOE, crossed compound parabolic concentrator (CCPC) lens.

Figure 1 depicts the schematic diagram of the proposed UHCPV system comprised of two optical elements: a NIDC (POE) and an array of CCPC lenses (SOEs). By considering the compactness of the system, a NIDC with a width \( D \) of about 100 cm has been designed to focus the sunlight onto the CCPC lenses at any focal distance \( F \) along the Z-axis. In order to achieve high solar concentration ratio, the NIDC consists of 480 facet mirrors to be arranged into twenty-two rows and twenty-two columns on the mechanical structure. Four mirrors in the central region of concentrator have been removed because of the shading of receiver. Flat facet mirrors with a dimension of 4 cm \( \times \) 4 cm are selected to form a total reflective area of 7680 cm\(^2\) and a total projection area of 7590 cm\(^2\). In order to avoid shadowing and blocking among the adjacent mirrors, the facet mirrors are gradually lifted from
central to peripheral regions of the dish concentrator. Besides, a small gap of 0.5 cm between the facet mirrors is required to absorb the manufacturing defect by providing tolerance for the installation of facets. The detailed design of NIDC has been patented and described in our previous works [9-11].

![Flow chart](image)

**Figure 2.** Flow chart shows the process of optimizing the design of UHCPV system.

3-D CCPC is designed by the intersection of two symmetric 2-D compound parabolic concentrators (CPCs) in orthogonal, and hence, it has a square-shaped entrance and exit apertures. Instead of using reflective CCPC, the CCPC lens that is made of B270 crown glass (refractive index, $n = 1.52$), has been utilized to further concentrate the sunlight reflected by NIDC from various angles onto the UHCPV receiver module that are equipped with a MJSC and a bypass diode. The advantages of dielectric-filled CCPC lens against reflective CCPC are twofold: (a) refraction at the air-dielectric interface improves the acceptance angle; (b) total internal reflection in the lens diminishes the
reflection loss. In this paper, a systematic method has been proposed to optimize the optical design of NIDC and CCPC lens that are incorporated into the UHCPV system. Figure 2 presents the process of optimizing the design of UHCPV system.

3. Optical design and analysis

3.1. Design of POE: non-imaging dish concentrator (NIDC)

In order to optimize the design of NIDC, an optical characterization of the NIDC has been carried out with the use of ray-tracing numerical simulation technique as presented in our previous works [12,13]. By assuming each facet mirror has a reflectivity of 93%, solar illumination on the receiver plane that is the entrance aperture of CCPC array, has been simulated by varying the $F/D$ ratio, where $F$ is the longest focal distance from the centre of receiver plane to the centre of NIDC and $D$ is the width of NIDC. In this study, the imperfection factors, i.e. circumsolar radiation and mirror surface slope error, are included in the simulation to avoid overestimation of output power. The seriousness of circumsolar radiation effect is rated in term of the circumsolar ratio ($\chi$) and the mirror surface slope error is reported in standard deviation ($\delta$) unit. The solar illumination on the receiver plane has been modelled for two different cases, namely ideal case ($\chi = 0$ and $\delta = 0$ mrad) and non-ideal case. The typical values of circumsolar ratio, $\chi = 0.2$ and slope error, $\delta = 2$ mrad are considered in the non-ideal case of this study. With the simulated solar illumination, the size of receiver can be optimized by minimizing the spillage loss of the NIDC.

Figures 3 and 4 present the simulation results of solar illumination in 2-D plots for both ideal and non-ideal cases respectively. The solar illumination is simulated at a $F/D$ ratio ranging from 0.5 to 1.5 with the increment of 0.1. By omitting the imperfection factors ($\chi = 0$ and $\delta = 0$ mrad), the NIDC is capable of producing uniform illumination area. The SCR at the central region of solar illumination is nearly constant (see figure 3). The higher the $F/D$ ratio the higher the SCR, ranging from 320 to 432 suns. Besides, the uniform illumination area reduces as the $F/D$ ratio increases. According to the simulated results of the non-ideal case ($\chi = 0.2$ and $\delta = 2$ mrad), the uniform illumination region narrows while the base region of flux distribution broadens as the $F/D$ ratio increases (see figure 4). For the non-ideal case, the SCR at the uniform illumination area does not significantly increases with the $F/D$ ratio higher than 1.0. This phenomenon happened because the energy at the central region of flux distribution spread towards outside the flux distribution. Figure 5 shows the comparison between

![Image](image_url)

**Figure 3.** The solar illumination in 2-D plots for ideal case ($\chi = 0$ and $\delta = 0$ mrad) at $F/D$ ratio ranging from 0.5 to 1.5.
the ideal case and the non-ideal case at $F/D$ ratio of 1.5. For the non-ideal case at $F/D$ ratio of 1.5, the SCR at the central region of flux distribution is much lower as compared to the ideal case. Therefore, overestimation of output power will be incurred if the imperfection factors are not considered in the concentrator design.

Spillage loss (percentage of sunray falling beyond the receiver) was determined by adopting different dimensions of square receiver plane. Figures 6 and 7 illustrate the spillage loss versus the receiver plane dimension (square in shape) for both ideal and non-ideal cases respectively at $F/D$ ratio ranging from 0.5 to 1.5. Practically, it is not a wise idea to design a receiver plane that just only covers the uniform illumination area, especially for the non-ideal case. According to the results, the spillage loss of non-ideal case for the receiver plane that just only covers the uniform illumination area

Figure 4. The solar illumination in 2-D plots for non-ideal case ($\chi = 0.2$ and $\delta = 2$ mrad) at $F/D$ ratio ranging from 0.5 to 1.5.

Figure 5. Comparison between the ideal case, i.e. $\chi = 0$ and $\delta = 0$ mrad (solid line) and the non-ideal case, i.e. $\chi = 0.2$ and $\delta = 2$ mrad (dotted line) at $F/D$ ratio of 1.5.
becomes very severe, as high as 78.7%, if the $F/D$ ratio increased to 1.5 (see figure 7). For the sake of minimizing the spillage loss and avoiding the oversizing of receiver, proper selection and detailed analysis of the receiver plane dimension are very important tasks in the concentrator design. In this study, the receiver plane with a dimension of 6 cm × 6 cm was chosen. As shown in figures 6 and 7, the selected receiver plane has a maximum spillage loss of 8.0% for both ideal and non-ideal cases.

**Figure 6.** Spillage loss versus receiver plane dimension (square in shape) for ideal case ($\chi = 0$ and $\delta = 0$ mrad) at $F/D$ ratio ranging from 0.5 to 1.5.

**Figure 7.** Spillage loss versus receiver plane dimension (square in shape) for non-ideal case ($\chi = 0.2$ and $\delta = 2$ mrad) at $F/D$ ratio ranging from 0.5 to 1.5.

3.2. Design of SOE: dielectric-filled CCPC lens

In this study, the dielectric-filled CCPC has been integrated with the NIDC to homogenize the non-uniform illumination distributed on the receiver plane and to further focus the sunlight concentrated by the NIDC onto MJSC. According to the simulated results as shown in figures 3 and 4, the NIDC is capable of producing symmetrical flux distribution that is much larger than the active area of a MJSC. Therefore, 2 × 2 arrays of UHCPV receiver modules were deployed to convert the highly concentrated
solar energy into electrical energy. This approach can diminish the current mismatch between the modules if they are interconnected in a series configuration. Figure 8 shows the cross-sectional view of the dielectric-filled CCPC lens. In order to match the dimension of optimized receiver plane, each UHCPV receiver module is bonded to a CCPC lens that has a square entrance aperture, \(2a = 3\) cm. In addition, the exit aperture of CCPC lens needs to be matched with the dimension of MJSC, whereby the exit aperture of CCPC can be bonded to the MJSC with an optical adhesive. The MJSC, with a dimension of \(1.0\) cm \(\times\) \(1.0\) cm, from Azur Space was deployed in this study [14]. By considering the practical limitations in assembly, the CCPC lens has an exit aperture, \(2a' = 0.98\) cm, which is slightly smaller than the dimension of the MJSC. With a refractive index \((n)\) of 1.52, the half acceptance angle of CCPC geometry, \(\theta_i' = 19.06^\circ\), the length of CCPC lens, \(L = 5.76\) cm, the half acceptance angle of CCPC lens \(\theta_i = 29.77^\circ\), and the geometrical concentration ratio of CCPC lens, \(C_{geo} = 9.37\) can be calculated by using the following equations as presented in our previous works [15,16].

\[
\theta_i' = \sin^{-1}\left(\frac{a'}{a}\right) \tag{1}
\]

\[
L = \frac{a'(1 + \sin \theta_i') \cos \theta_i'}{\sin^2 \theta_i'} \tag{2}
\]

\[
\theta = \sin^{-1}(n \sin \theta_i') \tag{3}
\]

\[
C_{geo} = \left(\frac{a}{a'}\right)^2 = \left(\frac{1}{\sin \theta_i}\right)^2 = \left(\frac{n}{\sin \theta_i}\right)^2 \tag{4}
\]

By assuming constant optical losses of 15\%, the effective concentration ratio of CCPC lens \((C_{SOE})\) is 7.97. The constant optical losses include the Fresnel reflection losses, absorption losses and some light rays escape from the side walls that are near to the exit aperture of CCPC lens.

As discussed in our previous works, the CCPC lens is designed in such a way that its angular acceptance angle \((2\theta)\) is greater than the rim angle of NIDC. This way can make sure that the CCPC lens can guide all the concentrated sunlight from NIDC to MJSC [15,16]. The rim angle \((\theta)\) can be calculated by using the following formula

\[
\theta = 2 \tan^{-1}\left(\frac{L_{xy}}{2L_c}\right) \tag{5}
\]

where \(L_{xy}\) is the distance of central points between the two most apart mirrors (the mirrors usually are positioned in opposite corners of the facet array), and \(L_c\) is the shortest distance in Z-direction from the central point of CCPC array to the distance line of \(L_{xy}\) (see figure 1).
As shown in figure 9, the rim angle of NIDC at $F/D$ ratio ranging from 0.5 to 1.5 has been calculated using equation (5). These calculated rim angles are essential for determine the optimal $F/D$ ratio that is smaller than the angular acceptance angle of CCPC lens. According to the results, there

![Figure 9. The calculated rim angles of NIDC at $F/D$ ratio ranging from 0.5 to 1.5.](image)

**Table 1.** The specification of the optimized UHCPV system.

| Primary optical element (POE): Non-imaging dish concentrator (NIDC) |  |
|---|---|
| Number of facet mirror | 480 units (arranged in 2-D array) |
| Dimension of facet mirror | 4 cm × 4 cm |
| Mirror Reflectivity | 93% |
| $F/D$ ratio | 1.4 |
| Total reflective area | 7680 cm$^2$ |
| Total projection area | 7590 cm$^2$ |
| Dimension of receiver plane | 6 cm × 6 cm |
| Rim angle, $\theta$ | 55.85° |

**Secondary optical elements (SOEs): dielectric-filled CCPC lens**

| Dielectric material | B270 crown glass |
| Refractive index, $n$ | 1.52 |
| Dimension of entrance aperture | 3 cm × 3 cm |
| Dimension of exit aperture | 0.98 cm × 0.98 cm |
| Length, $L$ | 5.76 cm |
| Half acceptance angle CCPC geometry, $\theta'_i$ | 19.06° |
| Angular half acceptance angle CCPC lens, $\theta_i$ | 29.77° |
| Optical losses | 15% |
| Geometrical concentration ratio of CCPC lens, $C_{geo}$ | 9.37 |
| Effective concentration ratio of CCPC lens, $C_{SOE}$ | 7.97 |
| Number of CCPC lens | 4 (arranged in 2 × 2 array) |

**Multi-junction solar cell (Azur Space product: 3C44 – 10 × 10 mm$^2$)**

| Typical efficiency at 1000 suns | 40.5% |
| Dimension of cell aperture | 10 mm × 10 mm |
| $V_{oc}$ at 1000 suns (1000 W/m$^2$ irradiance @ T = 25°C) | 3.14 V |
| $I_{sc}$ at 1000 suns (1000 W/m$^2$ irradiance @ T = 25°C) | 14.97 A |
| Maximum operating temperature | 110°C |
are only two rim angles of NIDC that are less than the angular acceptance angle of CCPC lens, $2\theta = 59.54^\circ$, namely $55.85^\circ$ and $52.34^\circ$ at $F/D$ ratio of 1.4 and 1.5 respectively. The $F/D$ ratio of 1.4 was chosen to design the NIDC since its spillage loss is lesser than the $F/D$ ratio of 1.5 for both ideal and non-ideal cases. Table 1 shows the specification of the optimized UHCPV system.

4. Electrical simulation and analysis

Before simulating the electrical performance of the UHCPV system, the effective SCR, $C_{\text{eff}}$ of each MJSC for both ideal ($\chi = 0$ and $\delta = 0$ mrad) and non-ideal ($\chi = 0.2$ and $\delta = 2$ mrad) cases at $F/D$ ratio of 1.4 was calculated by using equation (6). The MJSCs for both ideal and non-ideal cases have the effective SCR, $C_{\text{eff}}$ of 1563 suns and 1457 suns respectively.

$$C_{\text{eff}} = C_{\text{POE}} \times C_{\text{SOE}}$$  \hspace{1cm} (6)

where $C_{\text{POE}}$ is the average SCR of NIDC at the entrance aperture of CCPC lens, and $C_{\text{SOE}}$ is the effective concentration ratio of CCPC lens.

In this study, the electrical output power of the UHCPV system was simulated by using the Matlab/Simulink modeling. Both short-circuit current ($I_{\text{SC}}$) and open-circuit voltage ($V_{\text{OC}}$) of each MJSC can be modelled by the following equations:

$$I_{\text{SC}} = I^1_{\text{SC}} \times C_{\text{eff}}$$  \hspace{1cm} (7)

$$V_{\text{OC}} = V^1_{\text{OC}} + N \frac{kT}{q} \ln C_{\text{eff}}$$  \hspace{1cm} (8)

where $I^1_{\text{SC}}$ and $V^1_{\text{OC}}$ are the short-circuit current and open-circuit voltage of the MJSC under one sun respectively, $C_{\text{eff}}$ is the effective SCR of the MJSC, $N$ is the effective diode ideality factor, $T$ is the operating temperature (Kelvin), $k$ is the Boltzmann constant and $q$ is the electronic charge.

For this study, the MJSCs are assumed to have zero value in series resistance, $R_s = 0$ $\Omega$ and effective diode ideality factor, $N = 3$. According to the specification of Azur Space MJSC shown in table 1, the one sun short-circuit current ($I^1_{\text{SC}}$) and open-circuit voltage ($V^1_{\text{OC}}$) under standard test condition were calculated as 14.97 mA and 2.61 V respectively by using equations (7) and (8). The MJSCs are assumed to operate at the standard temperature of 298 Kelvin and the direct normal irradiance (DNI) level of 1000 W/m$^2$. After that, the maximum output power of the UHCPV system was simulated in MATLAB/Simulink platform system for both ideal and non-ideal cases. In this simulation, the UHCPV receiver modules are modelled to be connected in a series configuration.

Figure 10 shows the $I$-$V$ and $P$-$V$ curves of UHCPV system, which are simulated by using MATLAB/Simulink software, for the solar flux distribution of both ideal and non-ideal cases. As presented in figure 10, the maximum electrical output powers of both ideal and non-ideal cases are 259.3 W and 241.4 W respectively. There will be 7.4 % in overestimation of output power if the imperfection factors are not considered in the design of this UHCPV system. The DC system efficiency ($\eta_{\text{DC}}$) of UHCPV system can be calculated by the following equation:

$$\eta_{\text{DC}} = \frac{P_{\text{ele-max}}}{P_{\text{in}}} \times 100\%$$  \hspace{1cm} (9)

where $P_{\text{ele-max}}$ is the maximum electrical output power of the UHCPV system and $P_{\text{in}}$ is the input power of the UHCPV system. The input power of the system can be determined by multiplying both the total projection area of NIDC and DNI level. With a total projection area of 7590 cm$^2$ and DNI level of 1000 W/m$^2$, the DC system efficiency of both ideal and non-ideal cases are calculated as 34.2% and 31.8% respectively by using equation (9).
Figure 10. (a) I-V curve; (b) P-V curve for both ideal (χ = 0 and δ = 0 mrad) and non-ideal cases (χ = 0.2 and δ = 2 mrad) at F/D ratio of 1.4.

5. Conclusions
In this study, a systematic approach for optimizing the design of UHCPV system that integrated with two optical elements, i.e. NIDC and 3-D dielectric-filled CCPC lens. The NIDC can produce symmetrical and reasonably uniform solar illumination. The CCPC lens not only homogenizes the non-uniform flux distribution but also further focuses the reflected sunlight from NIDC onto MJSCs. The focal distance, spillage losses and rim angle of dish concentrator are the key parameters to get the optimal design of UHCPV system. In order to avoid the overestimation of output power, the simulation needs to consider the imperfection factors, i.e. mirror reflectivity of 93%, lens’ optical efficiency of 85%, circumsolar ratio of 0.2 and mirror surface slope error of 2 mrad. According to the results, the proposed UHCPV system can obtain effective ultra-high solar concentration ratio of 1475 suns and DC system efficiency of 31.8%. The DC system efficiency can be further improved by applying anti-reflective coating at the entrance aperture of CCPC lens to diminish the Fresnel reflection losses.
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