Space optimization of concentrator photovoltaic systems based on levelized cost of electricity in solar power plant

Li-Voon Oon¹, Ming-Hui Tan²*, Chee-Woon Wong¹, Tiong-Keat Yew², Kok-Keong Chong¹, Woei-Chong Tan¹ and Boon-Han Lim¹

¹ Lee Kong Chian Faculty of Engineering and Science, Universiti Tunku Abdul Rahman, Bandar Sungai Long, 43000 Kajang, Selangor, Malaysia.
² Faculty of Engineering and Green Technology, Universiti Tunku Abdul Rahman, Jalan Universiti, Bandar Barat, 31900 Kampar, Perak, Malaysia.
*Corresponding author’s E-mail address: mhtan@utar.edu.my

Abstract. Inappropriate layout design of concentrator photovoltaic (CPV) systems in the solar field will incur optical losses due to mutual shadowing among adjacent CPV systems. This will deteriorate the energy generation of a solar power plant (SPP). The trivial solution is to increase the separating distance between adjacent CPV systems. Unfortunately, it causes ineffectiveness in land usage and will be reflected to an increase in land-related costs. Therefore, optimization of layout design is an important procedure to determine the best trade-off between land usage and energy generation. The levelized cost of electricity (LCOE) of the SPP must be competitive to attract the interest of investors venturing into the solar energy business. A new computational algorithm has been proposed to optimized the field layout system of the CPV system by using the local weather data with the consideration of the shadowing effect. In this paper, a case study has been conducted in Kota Kinabalu, Malaysia to evaluate the performance of CPV systems in the SPP with different D/L ratios. The simulated results show that the optimized field layout for the CPV systems is at D/L ratio of 2.25, which accommodate the lowest value of LCOE.

1. Introduction
The improvement in power conversion efficiency of multi-junction solar cell has propagated the interest in concentrator photovoltaic (CPV) systems as an alternative to the conventional power generating system. According to Abdallah [1], dual-axis sun-tracking mechanism is essential to achieve maximum power generation. Dual-axis sun-tracking system is categorised into two types: azimuth-elevation sun-tracking system and tilt-roll (polar) sun-tracking system. According to Chong and Wong [2], the azimuth-elevation sun-tracking system is the most widespread sun-tracking method in various applications of harnessing solar energy.

The inappropriate layout design of CPV systems in the solar power plant will incur optical losses due to mutual shadowing among CPV systems and hence reduces electrical power generation. There are several methods used by researchers to reduce the mutual shadowing effect. In 2012, Perpiñán [3] modelled the mutual shadow geometry for dual-axis sun-tracking system for square array layout configuration. This study uses the trigonometry method to find the minimum separating distance to obtain zero-shadowing. Edgar et al. [4] also adopted the trigonometry method to calculate the minimum North-South spacing and East-West spacing for square array layout configuration of rectangular tracking systems. This method is less preferable as it will increase the land usage and only limited to the zero-shadowing condition. There is another method, i.e. ray-tracing method (point-to-
point method), introduced by Fartaria and Pereira [5] to determine the shadow losses for direct normal irradiance (DNI) of solar field for both square array layout configuration and staggered array layout configuration. However, this method needs a long computational time although the results obtained are accurate. Chong and Tan [6] developed a special algorithm which utilized the ray/plane algorithm (four-point method) to determine the shadowing and blocking effect for heliostat field in central tower system. With this approach, the computational time for the ray-tracing simulation can be reduced significantly.

As the solar energy technologies become more mature, the levelized cost of electricity (LCOE) is progressively being utilized to evaluate the economic feasibility of photovoltaic system projects to compare with other electricity generation technologies. The LCOE is an assessment parameter to evaluate the economic aspect of a power generation plant. Based on the aforementioned studies, the optimization of field layout design of PV system is only considering the system performance by reducing or eliminating the mutual shadowing among the PV system. To escalate the interest of investing in solar energy, the LCOE of the solar power plant must be reduced significantly. A comprehensive study to optimize the field layout of CPV systems based on the LCOE using the local weather data need to be done.

In this paper, a newly proposed computational algorithm has been developed to optimize the field layout design based on the LCOE using the local weather data. Conventionally, the mutual shadowing can be reduced by widening the separation between adjacent CPV systems in the array. However, this method needs more land area, and hence will lead to an increase in land-related costs. Therefore, the layout design of the solar power plant needs to be optimized in order to obtain the lowest LCOE. The separation between CPV systems is a trade-off between land use and productivity in which the economic balance between land cost and the cost of generation needed to be studied. The objective of this study is to optimize the field layout of CPV systems based on the LCOE using the local weather data.

2. Methodology

The methodology of optimization algorithm can be divided into three major steps: (a) To develop a computational algorithm to compute the shadowing effect of the dual-axis CPV sun-tracking systems, (b) To compute the shadowing effect of the dual-axis CPV sun-tracking systems, (c) optimization of field layout design by considering shadowing effect and LCOE using local weather data. The methodology to optimize the field layout design of the CPV system in the solar plant is depicted in Figure 1.
2.1. Sun-tracking angles
As the sun position varies throughout the day, dual-axis sun-tracking mechanism is vital to track the sun position in order to achieve the maximum energy generation for the CPV system. The sun-tracking method used in this study is Azimuth-Elevation sun-tracking method. In 2012, Chong and Tan [6] explained that the two sun-tracking angles, elevation angle, $\alpha$ and azimuth angle, $\beta$ can be computed by using the following equation:

$$\alpha = \sin^{-1}(\sin \delta \sin \Phi + \cos \delta \cos \omega \cos \Phi)$$

If $\cos \beta \geq 0$,

$$\beta^+ = \sin^{-1}\left[-\frac{\cos \delta \sin \omega}{\cos \alpha}\right]$$

else $\cos \beta < 0$,

$$\beta^- = \pi - \beta^+$$

where $\delta$ is the sun declination angle, $\omega$ is the hour angle, and $\Phi$ is the latitude.

2.2. Sun incident ray and ray/plane algorithm
To determine the shadow cast on the test CPV systems, the sun incident ray, $S$ needs to be known. After the instantaneous sun-tracking angles have been identified, the coordinate transformations are performed for both the adjacent blocking CPV systems (the CPV systems that cast shadow on the test CPV system) and test CPV system (the CPV system that is tested for shadowing effect) to simulate the instantaneous sun-tracking orientation of both CPV systems. The ray/plane algorithm is then applied to determine the area of the shadow cast by the adjacent blocking CPV systems on the surface of test CPV system [6] as illustrated in Figure 2.

Figure 2. Area of shadow caused by adjacent CPV system is computed using the ray/plane algorithm after performing the coordinate transformation for both CPV systems.

2.3. Field layout configuration
Figure 3 depicts a square array layout configuration with the specifications as listed in Table 1 is designed to perform the optimization study. In this study, the CPV systems are arranged in a square array manner with different spacing distance, $D$ within a designated specific square land area of 62500$m^2$. To generalize the spacing distance, $D/L$ ratio, which is the ratio of the spacing distance between the CPV systems to the diagonal length of the CPV system has been introduced.

In the simulation, the location of the test CPV system, which is the CPV system being shadowed by its adjacent CPV systems can be categorized into three different locations, edges E (four edges, e.g. top right, top left, bottom right and bottom left), sides S (four sides, e.g. right, left, top and bottom)
bottom) and center C. The number of adjacent CPV systems in which their shadows will be casted on the “test CPV system” for edges, sides and center are 3, 5 and 8 respectively.

| Table 1. Specification of the CPV system solar power plant |
|-------------|-----------------|-----------------|
| Location    | Kota Kinabalu, Malaysia |
| Land area   | 250 m × 250 m = 62500 m² |
| Sun-tracking method | Azimuth-Elevation |
| CPV system efficiency | 30% |
| Degradation rate | 0.5% |
| Size of the CPV system | 6m x 6m = 36 m² |
| D/L ratio | 1.50 | 1.75 | 2.00 | 2.25 | 2.50 |
| Total number of CPV system | 729 | 529 | 400 | 324 | 256 |

![Figure 3. The square array layout of the CPV system solar power plant and the different location of test CPV system. S: sides; E: edges; C: center.](image)

2.4. Energy generation

The energy generation for the solar power plant needs to be computed in order to calculate the LCOE. The energy generation can be computed by insert the local weather data, shadowing effect, CPV system efficiency, size of CPV system and total number of CPV system in a specific land area into Eqn. (2). In this case study, a time interval of 900 seconds (15 minutes) is selected to obtain a more accurate data collection.

\[
\text{Energy (kWh)} = \sum_{i=1}^{n} \sum_{j=1}^{96} \frac{\eta \times T \times DNI_j \times (1 - S_j) \times A}{3.6 \times 10^6} \tag{2}
\]

where \(n\) is the total number of CPV systems, \(\eta\) is the power conversion efficiency of CPV system, \(T\) is the time interval in seconds, \(DNI\) is the direct normal irradiance, \(S\) is the percentage area of shadowing and \(A\) is the size of the CPV system.

2.5. Levelized cost of electricity (LCOE)

There are a few important factors affecting the levelized cost of electricity (LCOE) of the solar power plant: (a) local weather data, (b) number of concentrators in a specific area of land, (c) total energy produced, (d) land-related costs, and (e) maintenance cost. Based on the review by Branker et al. [7], they had finalized and provided the proper equation to calculate the LCOE as shown in Eqn. (3). In
order to find the optimized layout design, the lowest possible value of LCOE computed for the CPV system solar power plant must be selected.

\[ LCOE = \frac{\sum_{t=0}^{T}(I_t + O_t + M_t + F_t)/(1 + r)^t}{\sum_{t=0}^{T}S_t(1 - d)^t/(1 + r)^t} \]  \hspace{1cm} (3)

where \( T \) is the lifespan of the systems in years, \( t \) is year, \( I_t \) is the CPV systems initial cost which comprising its manufacturing cost, construction cost, installation cost, etc., \( M_t \) is the maintenance costs of the CPV systems for \( t \) year, \( O_t \) is the operational costs of the CPV systems for \( t \) year, \( F_t \) is the interest expenditures of the CPV systems for \( t \) year, \( r \) is the discount rate of the CPV systems for \( t \) year, \( S_t \) is the yearly rated energy output of the CPV systems for \( t \) year and \( d \) is the degradation rate of the CPV systems.

3. Results and discussion
A case study has been carried out in Kota Kinabalu, Malaysia to optimize the layout design for the CPV systems in solar power plant. The simulation of the annual average percentage of shadowing and LCOE for the aforementioned case study is based on the specification as tabulated in Table 1.

The area of shadow cast on the test CPV system throughout the year is computed using the newly developed computational algorithm with an interval of 15 minutes. The annual energy generated by the CPV systems is also computed using the algorithm with the consideration of the shadowing effect for every 15 minutes throughout the year.

The D/L ratios are varied from 1.50 to 2.50 with an interval of 0.25. The D/L ratio of 1.50 is the minimum required separation ratio to avoid collision between the CPV systems. When the D/L ratio increases, the number of CPV systems within the designated specific area of land decreases. The number of CPV systems installed within the designated specific area for D/L ratio of 1.50, 1.75, 2.00, 2.25 and 2.50 are 729, 529, 400, 324 and 256 respectively.

According to Figure 4, the annual total average percentage area of shadowing reduces as the D/L ratio increases. This proves that wider the spacing distance between CPV systems will produce lesser shadowing effect. Unfortunately, this will increase the land utilization and leads to an increase in land-related costs. Therefore, the best way to optimize the field layout design is to compare D/L ratios which producing the lowest LCOE.

The LCOE of each D/L ratio is calculated using Eqn. (3) based on the specification as listed in Table 2. In this paper, the interest expenditure is assumed to be zero as no loan will be applied to finance this solar power plant and no incentives will be considered. The simulated results for LCOE versus different D/L ratios were depict in Figure 4. It shows that the optimal layout design for this case study is at D/L ratio of 2.25, which has a LCOE value of RM1.332/kWh despite its annual average percentage area of shadowing is not the lowest. This can conclude that it is important to consider the LCOE in the optimization of field layout design in order to determine the minimum cost per kWh of the solar power plant. The aforementioned methodology can be referred as a guideline for researchers and engineers to optimize the field layout design of the CPV system solar power plant which provide the lowest LCOE.

| Table 2. The parameters applied for the calculation of LCOE on the CPV systems. |
|---------------------------------------------------------------|
| **Initial cost (excluding cost of CPV systems)** | RM 3,463,722 |
| **Discount rate** | 3% |
| **Lifespan of CPV system, t** | 25 years |
| **Interest expenditure for t years** | 0% |
| **Cost per CPV tracker** | RM 130,000 |
4. Conclusion
A systematic approach using the computational algorithm to optimize the layout design of CPV system based on LCOE has been developed with the consideration of both the shadowing effect and local weather data. The methodology for analysing the shadowing effect of the dual-axis CPV system has been analysed in details. The simulation results show that the CPV solar power plant with a D/L ratio of 2.25 has the lowest value of LCOE despite its annual average percentage area of shadowing is not the lowest. As a conclusion, it is worthwhile to include LCOE as an essential factor in the layout design to achieve the comprehensive economic balance between cost and power generation.

5. Acknowledgements
The authors would like to express their sincere gratitude to UTAR Research Fund 2017 Cycle 2 with project number IPSR/RMC/UTARRF/2017-C2/T04 (vote account 6200/TD5) for their financial support. In additions, the authors also would like to express their gratitude to the Ministry of Energy, Green Technology and Water (AAIBE Trust Fund) with vote account 4356/001.

6. References
[1] S. Abdallah, “The effect of using sun tracking systems on the voltage–current characteristics and power generation of flat plate photovoltaics,” *Energy Convers. Manag.*, vol. 45, no. 11–12, pp. 1671–1679, Jul. 2004.
[2] K. K. Chong and C. W. Wong, “General formula for on-axis sun-tracking system and its application in improving tracking accuracy of solar collector,” *Sol. Energy*, vol. 83, pp. 298–305, 2008.
[3] O. Perpiñán, “Cost of energy and mutual shadows in a two-axis tracking PV system,” *Renew. Energy*, vol. 43, pp. 331–342, 2012.
[4] R. Edgar, Z. Stachurski, and S. Cochard, “Optimising direct normal insolation of rectangular PV platforms,” *Sol. Energy*, vol. 136, pp. 166–173, 2016.
[5] T. Oliveira Fartaria and M. Collares Pereira, “Simulation and computation of shadow losses of direct normal, diffuse solar radiation and albedo in a photovoltaic field with multiple 2-axis trackers using ray tracing methods,” *Sol. Energy*, vol. 91, pp. 93–101, 2013.
[6] K. K. Chong and M. H. Tan, “Comparison study of two different sun-tracking methods in optical efficiency of heliostat field,” *Int. J. Photoenergy*, vol. 2012, 2012.
[7] K. Branker, M. J. M. Pathak, and J. M. Pearce, “A review of solar photovoltaic levelized cost of electricity,” *Renew. Sustain. Energy Rev.*, vol. 15, no. 9, pp. 4470–4482, 2011.