CHEMICAL ENGINEERING TRANSACTIONS

VOL. 83, 2021

A publication of AIDIC

The Italian Association of Chemical Engineering
Online at www.cetjournal.it

Guest Editors: Jeng Shiun Lim, Nor Alafiza Yunus, Jiří Jaromír Klemeš

ISBN 978-88-95608-81-5; **ISSN** 2283-9216

DOI: 10.3303/CET2183019

Optimization of Photovoltaic Array Orientation and Performance Evaluation of Solar Tracking Systems

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In recent years, solar energy has received tremendous attention in accordance with the global efforts in moving towards clean energy generation. A solar tracking system shifts the position of solar panel following the Sun’s movement, allowing more energy to be harvested. This paper aims to evaluate the performance of solar tracking system in Malaysia, including the east-west single-axis tracking system, north-south single-axis tracking system, vertical axis tracking system, and dual-axis tracking system. The periodical tilt angle adjustment of fixed-tilt photovoltaic system is also investigated to optimize its performance. A mathematical model is formulated to compute the amount of solar radiation collected in a photovoltaic system and the optimization model is solved using genetic algorithm to determine the optimal tilt and azimuth angles for maximum solar radiation yield. Based on the results, PV system with dual-axis solar tracker has 22.14 % more solar radiation collected compared to the fixed-tilt system, while monthly tilt angle adjustment improves the yield by 2.15 %.

1. Introduction

Global climate change has urged the transition of energy system from fossil-fuel to renewable-based. Solar energy which is free and abundant in Malaysia has the potential to satisfy Malaysia energy requirement (Khaliludin et al., 2020). The conversion of solar radiation into electricity can be done using solar photovoltaic (PV) modules, where the power output is dependent on the amount of solar radiation collected. Optimizing the tilt angle of PV modules has a limited yield improvement as the position of Sun varies with time in a day despite the fixed position of PV modules. This bottleneck can be overcome using solar tracker which allows the solar collectors to accurately point towards the sun and compensate for time changes observed in altitude, azimuth and latitude angles of the sun (Nsengiyumva et al., 2018). Solar tracking systems can be classified into single-axis tracking system and dual-axis tracking system based on their movement degree of freedom (Awasthi et al., 2020). A single-axis system has only one degree of freedom for the axis of rotation, it usually consumes less energy and is less complex compared to a multi-axis system (Sumathi et al., 2017). A dual-axis solar tracking system (DAT) tracks the sun in two different axes using two pivot points to rotate. It is superior in tracking the yearly sun movement such as the altitude of sun from season to season, making it more efficient and has higher solar energy gain (Hafez et al., 2018).

In the past, a few studies have been conducted to optimize the slope of PV array in Malaysia: Khatib et al. (2015) calculated the monthly and seasonal optimum tilt angles for five sites in Malaysia using Liu and Jordan (1963) model, Fadaeenejad et al. (2015) adopted Liu and Jordan (1963) model to determine the optimal PV array slope for three villages in Malaysia, Ahmed et al. (2019) assessed the PV yield of south- and north-facing solar panel subjected to various tilt angles, Abdul-Razak et al. (2019) evaluated the electricity output of terrace-based housing cohort orientated along the northwest-southeast axis, north-south axis, northeast-southwest axis, and east-west axis. These studies identified the optimal collector slope by substituting the values manually or through simulation method, which makes the solving process inefficient. Besides, some studies only investigated a limited range of angles and the final result only represents the best angle within a given range, but not necessarily the optimal value. The effect of solar tracking system to the solar radiation yield was studied by Alkaff et al. (2019) who compared the performance of single-axis tracking systems, two-

Paper Received: 30/06/2020; Revised: 28/08/2020; Accepted: 28/08/2020
Please cite this article as: Mah A.X.Y., Ho W.S., Hassim M.H., Hashim H., 2021, Optimization of Photovoltaic Array Orientation and Performance Evaluation of Solar Tracking Systems, Chemical Engineering Transactions, 83, 109-114 DOI:10.3303/CET2183019

axis tracking system and the fixed south-oriented PV system. However, the periodical adjustment of tilt angle for the fixed-tilt system is not considered. Adjusting the tilt angle manually could maximize the yield of a fixed-tilt system and the relevant study would provide a more comprehensive comparison of different PV system types.
This study aims to provide a comprehensive performance evaluation of solar tracking system in Malaysia by comparing the yield of PV system with and without solar trackers. Genetic algorithm (GA) will be employed to determine the optimal tilt and azimuth angles of solar panels instead of the conventional simulation methods. For this optimization problem with complex nonlinear variables, GA is able to find the global optimum solution with a high probability (Yadav and Chandel, 2013). While the PV tilt angle is often discussed, the optimization of azimuth angle is also considered in this work as it will impact the yield. The feasibility of monthly tilt angle adjustment is investigated by determining the optimal slope in every month and identifying the annual yield.

2. Methodology

This section discusses the problem statement and mathematical model used in this study. In the mathematical model, all the angles are expressed in degrees unless otherwise specified.

2.1 Problem statement

The types of PV systems being studied are demonstrated in Figure 1, including fixed-tilt system with optimal slope (FO), monthly optimal slope adjustment (MO), east-west single-axis tracking system (EWSAT), north-south single-axis tracking system (NSSAT), vertical single-axis tracking system (VSAT) and dual-axis tracking system (DAT). Given the typical meteorological year (TMY) solar radiation data, the tilt and azimuth angles of the PV systems are optimized to collect the maximum amount of solar radiation on the PV surface.

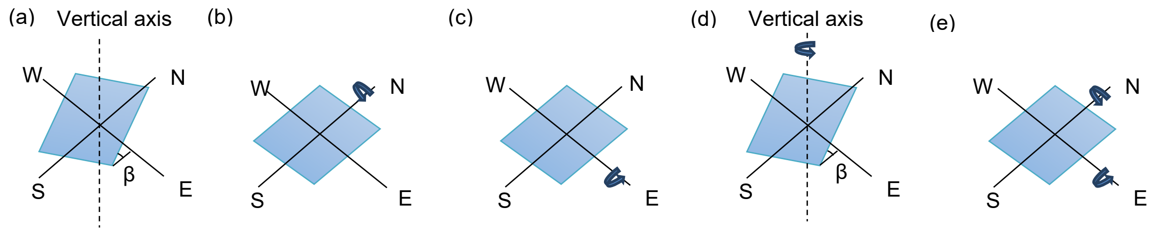

Figure 1: PV system with (a) fixed tilt (FO or MO) (b) EWSAT (c) NSSAT (d) VSAT (e) DAT

2.2 Mathematical model

The main objective of this optimization model is to maximize the solar radiation incident on the PV array by optimizing the tilt angle and azimuth angle of the collecting surface. The annual solar radiation received by PV array is equivalent to the sum of hourly solar radiation on each day, as shown in Eq(1), where I^{Annual} is the total solar radiation incident on the PV array in a year and $I_{d,t}^{\text{Day}}$ is the amount of solar radiation incident on the PV array at local time *t* on day *d*.

$$I^{\text{Annual}} = \sum_{d,t} I_{d,t}^{\text{Day}} \tag{1}$$

Solar time is the time based on the apparent angular motion of the sun across the sky, and it is used in all of the sun-angle relationships. Eq(2) can be used to convert local time of a region to solar time, where $\text{ST}_{d,t}$ is the solar time at local time *t* on day *d*, LT_t is the local time, LONG is the longitude of the location, TZ is the time zone and E_d is the equation of time. The equation of time can be calculated using Eqs(3) and (4) as proposed by Spencer (1971), where n_d is the day number in a year.

$$\text{ST}_{d,t} = \text{LT}_t + \frac{\text{LONG}}{15} - \text{TZ} + \text{E}_d \qquad \forall d,t \tag{2}$$

$$\text{E}_d = \frac{229.2}{60}(0.000075 + 0.001868 \cos \text{B}_d - 0.032077 \sin \text{B}_d - 0.014615 \cos 2\text{B}_d - 0.04089 \sin 2\text{B}_d) \qquad \forall d \tag{3}$$

$$\text{B}_d = \frac{360}{365}(\text{n}_d - 1) \qquad \forall d \tag{4}$$

Solar declination angle, δ_d can be approximated through Eq(5) as proposed by Cooper (1969). Eqs(6) to (8) show the expression for hour angle ($\omega_{d,t}$), zenith angle ($\theta^z_{d,t}$) and solar azimuth angle ($\gamma^s_{d,t}$), where ϕ is the latitude of the location studied.

$$\delta_d = 23.45 \sin\left[\frac{360}{365}\,(284 + n_d)\right] \qquad \forall d \tag{5}$$

$$\omega_{d,t} = 15\ \times (12 - ST_{d,t}) \qquad \forall d,t \tag{6}$$

$$\theta^z_{d,t} = \cos^{-1}\left(\cos\phi\ \cos\delta_d\ \cos\omega_{d,t} +\ \sin\phi\ \sin\delta_d\right) \qquad \forall d,t \tag{7}$$

$$\gamma^s_{d,t} = \sin^{-1}\left(\frac{\cos\delta_d \sin\omega_{d,t}}{\sin\theta^z_{d,t}}\right) \qquad \forall d,t \tag{8}$$

The angle of incidence, $\theta_{d,t}$ represents the angle between the beam radiation on a surface and the normal to that surface, its calculation is shown in Eq(9), where $\beta_{d,t}$ is the collector tilt angle at local time *t* on day *d* and $\gamma_{d,t}$ is the collector azimuth angle at local time *t* on day *d*.

$$\theta_{d,t} = \cos^{-1}\left[\cos\theta^z_{d,t}\cos\beta_{d,t} + \left(1 - \cos\theta^z_{d,t}\right)\left(1 - \cos\beta_{d,t}\right)\cos\left(\frac{\gamma^s_{d,t}}{\gamma_{d,t}}\right)\right] \qquad \forall d,t \tag{9}$$

This study adopts the third generation of solar radiation model proposed by Perez et al. (1990) to estimate the amount of solar radiation incident on the PV surface. The total amount of solar radiation incident on a PV panel is obtained through the summation of direct beam radiation, diffuse radiation and reflected radiation as illustrated in Eq(10), where $I^{Bp}_{d,t}$ is the direct beam radiation incident on PV panel at local time *t* on day *d*, $I^{Dp}_{d,t}$ is the diffuse radiation incident on PV panel at local time *t* on day *d* and $I^{Rp}_{d,t}$ is the reflected radiation incident on PV panel at local time *t* on day *d*.

$$I^{Day}_{d,t} = I^{Bp}_{d,t} + I^{Dp}_{d,t} + I^{Rp}_{d,t} \qquad \forall d,t \tag{10}$$

Eq(11) shows direct beam radiation calculation, where $I^{Bn}_{d,t}$ is direct normal irradiance obtained from TMY data.

$$I^{Bp}_{d,t} = I^{Bn}_{d,t}\cos\theta_{d,t} \qquad \forall d,t \tag{11}$$

The reflected radiation is computed through Eq(12), where $I^{Gh}_{d,t}$ is the global horizontal irradiance at local time *t* on day *d*, $I^{Dh}_{d,t}$ is the diffuse horizontal irradiance at local time *t* on day *d* obtained from TMY data and ρ is the surface albedo that is set as 0.2.

$$I^{Rp}_{d,t} = I^{Gh}_{d,t}\,\rho\left(\frac{1-\cos\beta_{d,t}}{2}\right) \qquad \forall d,t \tag{12}$$

$$I^{Gh}_{d,t} = I^{Bn}_{d,t}\cos\theta^z_{d,t} + I^{Dh}_{d,t} \qquad \forall d,t \tag{13}$$

In Perez model, several coefficients are required for estimating the diffuse radiation on PV surface. First, the clearness index, $\varepsilon_{d,t}$ is obtained through Eq(14). The air mass is calculated using the formula of Kasten and Young (1989) as in Eq(15). The extra-terrestrial radiation (Duffie and Beckman, 1991) is given by Eq(16). With the above parameters, the brightness, $\Delta_{d,t}$ can be calculated using Eq(17).

$$\varepsilon_{d,t} = \frac{\left(\frac{I^{Dh}_{d,t}+I^{Bn}_{d,t}}{I^{Dh}_{d,t}}\right)+5.535\times10^{-6}\times\left(\theta^z_{d,t}\right)^3}{1+5.535\times10^{-6}\times\left(\theta^z_{d,t}\right)^3} \qquad \forall d,t \tag{14}$$

$$m_{d,t} = \frac{1}{\cos\theta^z_{d,t}+0.5057\left(96.08^\circ-\theta^z_{d,t}\right)^{-1.634}} \qquad \forall d,t \tag{15}$$

$$I^e_d = 1367\ \left[1 + 0.033\cos\left(\frac{360\ n_d}{365}\right)\right] \qquad \forall d \tag{16}$$

$$\Delta_{d,t} = \frac{m_{d,t}\,I^{Dh}_{d,t}}{I^e_d} \qquad \forall d,t \tag{17}$$

Once brightness is identified, the brightness coefficients $F^1_{d,t}$ and $F^2_{d,t}$ can be obtained using Eqs (18) and (19). $f^{11}_{d,t}$ to $f^{23}_{d,t}$ represents the coefficients for Perez diffuse radiation model, their values vary with the clearness index $\varepsilon_{d,t}$ as shown in Table 1. Finally, the diffuse radiation on an inclined surface is given by Eq(20), where the values of a and b can be computed via Eqs (21) and (22).

$$F_{d,t}^{1} = \max(0, f_{d,t}^{11} + f_{d,t}^{12}\,\Delta_{d,t} + f_{d,t}^{13}\theta_{d,t}^{z}\frac{\pi}{180}) \quad \forall d,t \tag{18}$$

$$F_{d,t}^{2} = f_{d,t}^{21} + f_{d,t}^{22}\,\Delta_{d,t} + f_{d,t}^{23}\theta_{d,t}^{z}\frac{\pi}{180} \quad \forall d,t \tag{19}$$

$$I_{d,t}^{Dp} = I_{d,t}^{Dh}\left[\left(1 - F_{d,t}^{1}\right)\left(\frac{1+\cos\beta_{d,t}}{2}\right) + F_{d,t}^{1}\frac{a}{b} + F_{d,t}^{2}\sin\beta_{d,t}\right] \quad \forall d,t \tag{20}$$

$$a_{d,t} = \max(0, \cos\theta_{d,t}) \quad \forall d,t \tag{21}$$

$$b_{d,t} = \max(\cos 85°, \cos\theta_{d,t}^{z}) \quad \forall d,t \tag{22}$$

Table 1: Coefficients for Perez model (Perez et al., 1990)

$\varepsilon_{d,t}$	$f_{d,t}^{11}$	$f_{d,t}^{12}$	$f_{d,t}^{13}$	$f_{d,t}^{21}$	$f_{d,t}^{22}$	$f_{d,t}^{23}$
1–1.065	-0.008	0.588	-0.062	-0.060	0.072	-0.022
1.065–1.230	0.130	0.683	-0.151	-0.019	0.066	-0.029
1.230–1.500	0.330	0.487	-0.221	0.055	-0.064	-0.026
1.500–1.950	0.568	0.187	-0.295	0.109	-0.152	0.014
1.950–2.800	0.873	-0.392	-0.362	0.226	-0.462	0.001
2.800–4.500	1.132	-1.237	-0.412	0.288	-0.823	0.056

For each PV system, the collector slope and azimuth angle vary in different ways as shown in Table 2. For fixed-tilt system, the tilt and azimuth angles are constant throughout the year, as represented by the fixed values β and γ. For monthly tilt angle adjustment, β_m describes the variation in slope angle by month *m*. For PV systems with solar trackers, the tilt and azimuth angles vary with time and only the slope of VSAT is fixed.

Table 2: Collector tilt and azimuth angles of various PV systems

System Type	Collector Tilt Angle	Collector Azimuth Angle
FO	$\beta_{d,t} = \beta$	$\gamma_{d,t} = \gamma$
MO	$\beta_{d,t} = \beta_m$	$\gamma_{d,t} = \gamma$
EWSAT	$\beta_{d,t} = \tan^{-1}\left[\tan\theta_{d,t}^{z}\ \lvert\cos(\gamma_{d,t} - \gamma_{d,t}^{s})\rvert\right]$	$\gamma_{d,t} = \begin{cases} 90° & \text{if } \gamma_{d,t}^{s} > 0 \\ -90° & \text{if } \gamma_{d,t}^{s} \le 0 \end{cases}$
NSSAT	$\beta_{d,t} = \tan^{-1}\left[\tan\theta_{d,t}^{z}\ \lvert\cos\gamma_{d,t}^{s}\rvert\right]$	$\gamma_{d,t} = \begin{cases} 0° & \text{if } \lvert\gamma_{d,t}^{s}\rvert < 0 \\ 180° & \text{if } \lvert\gamma_{d,t}^{s}\rvert \ge 0 \end{cases}$
VSAT	$\beta_{d,t} = \beta$	$\gamma_{d,t} = \gamma_{d,t}^{s}$
DAT	$\beta_{d,t} = \theta_{d,t}^{z}$	$\gamma_{d,t} = \gamma_{d,t}^{s}$

For EWSAT, NSSAT and DAT, the tilt and azimuth angles of PV panel have been defined through equations, and the optimization through genetic algorithm solver is not required. The azimuth angle of VSAT is defined but its slope is a variable which requires optimization via genetic algorithm solver. For FO and MO PV system, optimization tool is needed to find out the optimal collector slope and azimuth angle.

3. Case study

In this study, the performance of different PV systems in Johor Bahru, Malaysia (1.495 N, 103.755 E) is being evaluated. The time zone for the study location is GMT+8. The hourly diffuse horizontal irradiance (DHI) and direct normal irradiance (DNI) data for the given location are retrieved from PVGIS (2019) in TMY format. TMY is a set of meteorological data with data values for every hour in a year for a given geographical location. The TMY data extracted from PVGIS is based on the hourly data within the period of 2007 to 2016.

4. Result and discussion`

Table 3 shows the optimal values of tilt and azimuth angles obtained using genetic algorithm solver in MATLAB Global Optimization Toolbox (The MathWorks, 2019). Based on the results, the optimal slope and azimuth for a fixed PV panel is 5° and -78°. For northern hemisphere, an azimuth value of zero means the collector is facing the equator (south), +90° means the collector is facing west, –90° means the collector is facing east, and +/-180° represents the collector is facing north. For PV system with monthly adjustment, the optimal azimuth angle is -180° (north-facing) and the optimal tilt angle by month is displayed in Table 3. The optimal slope for vertical axis tracking system is 37°.

Table 3: Optimal tilt and azimuth angles for PV systems

Scenario	Optimal Tilt Angle (°)	Optimal Azimuth Angle (°)
FO	5	-78
MO	0,0,0,12,21,29,25,17,0,0,0,0 (by month)	-180
VSAT	37	Varies continuously

Table 4 shows the annual yield of each PV system, where the fixed optimal PV system is used as a baseline to evaluate the yield improvement of other systems. Overall, dual-axis tracking system raises the yield most significantly (22.14 %), followed by VSAT (17.98 %), EWSAT (16.73 %), NSSAT (4.63 %) and MO (2.15 %).

Table 4: Solar radiation yield

	FO	MO	NSSAT	EWSAT	VSAT	DAT
Solar radiation collected ($kWh/m^2/y$)	1,696	1,733	1,775	1,980	2,001	2,072
Yield improvement (%)	-	2.15	4.63	16.73	17.98	22.14

Figure 2a shows the annual average hourly solar radiation collected by the PV systems in a day, and it can be observed that the effect of solar trackers (DA, EWSAT, VSAT) is more significant in the morning and evening, and less obvious at noon (12 am to 2 pm). The NSSAT performs slightly better than the fixed-tilt system but its yield is much lower than other tracking systems. Figure 2b presents the solar radiation collected by month, where the dual-axis tracking system performs the best in general. VSAT and EWSAT outperform each other at different timings, EWSAT generally performs better in March, April, August and September while VSAT performs better during the rest of the year. All PV systems with solar trackers perform significantly better than the system without solar trackers.

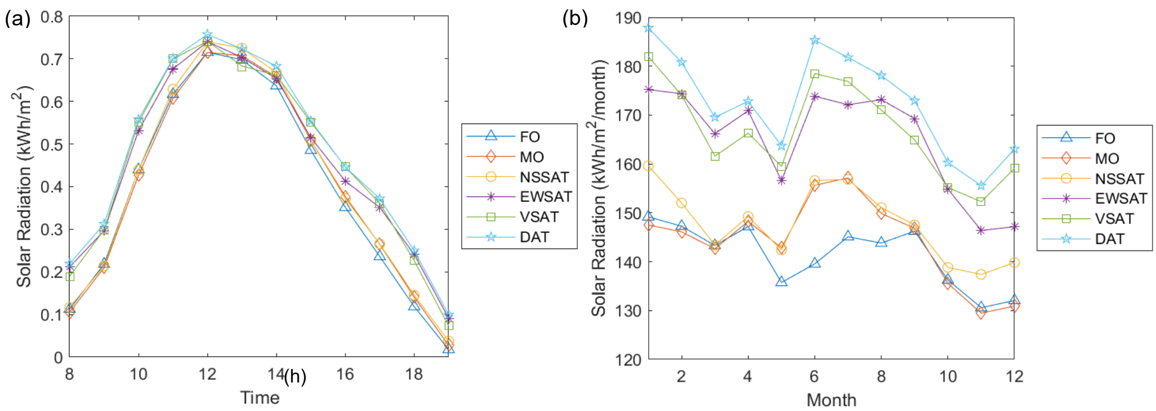

Figure 2: (a) Average hourly solar radiation collected (b) Total solar radiation collected by month

5. Conclusions

In this study, the optimal tilt and azimuth angle of the PV array has been determined followed by the performance evaluation of solar tracking system in Malaysia. A mathematical model is developed to optimize the collector tilt and azimuth angles. The optimization model is then solved using genetic algorithm. Based on the results, dual-axis tracking system has the greatest energy gain followed by vertical axis tracking, east-west tracking, north-south tracking, fixed-tilt system with monthly adjustment, and fixed-tilt system without adjustment. Overall, PV systems with solar trackers perform better than the system without solar trackers. Although solar tracking system does improve the solar radiation yield, the economic performance should be further investigated in the future study. The future work should also consider the declining performance of PV system with increasing temperature when targeting the PV system for electricity generation.

Acknowledgements

The authors would like to acknowledge the research grants from Universiti Teknologi Malaysia with grant no. Q.J130000.3051.02M03, R.J130000.7651.4C298, Q.J130000.2851.00L51, Q.J130000.3551.06G47 and Q.J130000.3551.05G50.

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