Optimal Bifacial Solar Panel Tilt Angle Using Meteorological Data

Hammad Hasan, *Member, IEEE,* Ameena Saad Al-Sumait, *Senior Member, IEEE,*

***Abstract*—This article explores the optimization of bifacial solar panel orientation, aiming to reconcile their superior efficiency with the associated higher costs. Leveraging optimization techniques, we propose a universal and systematic method to determine the optimal tilt angle and azimuth orientation for bifacial solar panels. This approach seeks to strike a balance between maximizing energy absorption and addressing economic considerations, providing a versatile framework applicable across diverse scenarios and geographical locations. The goal is to empower solar energy practitioners with a data-driven tool that enhances the overall performance of bifacial solar systems, making them a more compelling and economically viable choice for sustainable energy solutions.**

***Index Terms*—Bifacial, Optimization, Albedo, Bifacial gain**

I. Introduction

THE bifacial photovoltaics (PV) technology promises several advantages over mono-facials, including improved energy yield, and lower operating temperature [1]. The goal of this article is to find the optimal configuration and parameters for the bifacial panels. The effectiveness of bifacial solar panels in converting sunlight into electricity is strongly influenced by the intensity of direct sunlight, the albedo of the ground surface beneath the panels, and the amount of light reflected from the ground onto the rear surface of the panels. [2].

The adoption of bifacial solar cells is gaining traction in the market, fueled by ongoing research and development in the field. Unlike monofacial panels that can only capture sunlight from the front, bifacial panels have the ability to harness solar radiation from both the front and rear sides. This enhanced light absorption capacity enables bifacial panels to generate up to 30% more energy compared to their monofacial counterparts, resulting in increased energy output with reduced material consumption and land usage [3]. While bifacial solar panels incur a marginally higher cost compared to monofacial panels, their superior energy generation capacity ultimately translates into a more cost-effective investment. [4]. The efficiency gain of a bifacial solar system compared to a monofacial system can vary significantly depending on the system design, environmental conditions, and the optical properties of the bifacial solar panels. The bifaciality of the panel, which is the ability to generate electricity from both the front and back surfaces, plays a crucial role in this gain. Additionally, external factors like the albedo of the ground beneath the panels and the mounting details of the system can significantly impact the overall performance of a bifacial solar system [5].

$$\text{Bifaciality Factor} = (\eta_{\text{front}} \cdot \eta_{\text{rear}}) \times 100\% \tag{1}$$

$$BG_E = \frac{E_{\text{bifacial}}}{E_{\text{mono}}} - 1 \tag{2}$$

where:

BG_E is the Bifacial Gain

E_{bifacial} is the energy generation of bifacial panels

E_{mono} is the energy generation of monofacial panels

The bifacial gain depends on the location, angle, and radiation of the module. Bi-facial modules cost more than mono-facial modules. Due to this higher cost compared to mono-facial modules, consideration of bi-facial modules for a project necessitates extensive performance and economical evaluation.

II. Literature Review

Bifacial photovoltaic (PV) technology has garnered significant attention in recent years due to its potential to enhance solar panel efficiency. This section provides an overview of the existing literature on bifacial solar panels, focusing on the key aspects, challenges, and optimizations in this field.

This study presents an in-depth analysis of a vertically oriented bifacial solar photovoltaic (PV) module using design and simulation techniques. It also included financial analysis and 3D modelling of the system [6]. In [7], the author demonstrates that the implementation of bifacial modules in fixed-tilt solar systems can yield up to a 30% increase in annual energy production compared to their monofacial counterparts. This enhanced energy yield can be further amplified to over 40% by employing bifacial modules in conjunction with simple single-axis tracking systems. The bifacial gain can be further increased by using optical systems redirecting diffuse and direct solar radiation to the rear of the solar cell without solar tracking [8].
Another study in [9] highlights the latest intelligent optimization techniques employed in solar energy systems, delving into their functionalities, limitations, research gaps, and contributions. The review concludes that the primary goals of optimization methods are to minimize investment, operational, and maintenance costs while simultaneously reducing emissions and enhancing system reliability. However, these studies have primarily focused on monofacial solar panels. Further, [10] and [11] developed a stochastic-heuristic methodology considering solar irradiation, temperature, wind speed to minimize the investment and operational costs.

To identify the most optimal combinations of system parameters, this study in [12] comprehensively reviews and analyzes the design of photovoltaic (PV) power plant optimization strategies based on current literature. The study also explores component sizing for PV power plants, including the tilt angle of PV modules, inverters, transformers, and cables. The Physics-based empirical models in [13] could be used to optimize the design of these technologies and lower the levelized cost of electricity (LCOE).

To maximize the electricity yield of bifacial modules, three critical design parameters must be considered: elevation (E), azimuth angle (γ_M), and tilt angle (β). These parameters are interrelated, and the ideal azimuth and tilt angles depend on the elevation. Research also suggests that ground-mounted, vertical, east-west-facing bifacial modules will outperform their south-north-facing, for an albedo of 0.5, for below the latitude of 30. The empirical equations are mentioned below in the formula sheet. There are also different methodologies to find the optimal values or just use the traditionally used values.

The existing literature primarily focuses on optimizing bifacial PV systems for specific geographic locations or specialized configurations, such as vertical installations. However, it remains challenging to extrapolate these location- and configuration-specific findings to establish a universally optimized performance framework for this technology.

This research features a custom objective function and uses the old data from a specific point. This method has advantages over PVSyst in finding optimal angles due to more control. Features that can be set include: using forecasting models, choosing the desired amount of input data, and model accuracy can be increased.

III. Problem Formulation

The objective of this optimization problem is to determine the optimal tilt angle (β) and azimuth angle (γ) for a photovoltaic (PV) solar panel system, with the goal of maximizing the total incident solar radiation on the PV modules. The optimization is based on a mathematical model that considers direct sunlight, reflection losses, and various angle-dependent factors. The azimuth angle is mostly south-facing for the UAE, which is zero. It can be removed from the analysis which gives a faster and more accurate answer.

A. Variables

$$\beta : \text{Tilt angle of the solar panel (in radians)}$$
$$\gamma : \text{Azimuth angle of the solar panel (in radians)}$$

B. Objective Function

The objective is to maximize the total incident solar radiation (Z) on the PV modules, which is influenced by the direct sunlight and reflection losses. The objective function is defined as:

$$Z = (1 - F_A) \cdot (1 - F_D) \cdot (I_{\text{Direct\_Front}} + I_{\text{Direct\_Rear}})$$

where:

$$\begin{aligned} F_A &: \text{Angle-dependent factor (front side)} \\ F_D &: \text{Angle-dependent factor (rear side)} \\ I_{\text{Direct\_Front}} &: \text{Direct solar radiation incident on the front} \\ I_{\text{Direct\_Rear}} &: \text{Direct solar radiation incident on the rear} \end{aligned}$$

The negative of Z is used as the objective function in the optimization, as the `minimize` function in scipy aims to minimize the objective.

C. Constraints

1) **Tilt Angle Constraints:**

$$\beta \geq 0.01 \, \text{radians} \quad \text{(to avoid near-horizontal angles)}$$
$$\beta \leq \frac{\pi}{4} \, \text{radians} \quad \text{(to limit the tilt angle to 45 degrees)}$$

2) **Azimuth Angle Constraints:**

$$\gamma \geq 0 \, \text{radians}$$
$$\gamma \leq \pi \, \text{radians} \quad \text{(south-facing)}$$

3) **Angle-Dependent Factor Constraints:**

$$F_A \leq F_{A_{\text{max}}} \quad \text{(where } F_{A_{\text{max}}} \text{ is a predefined maximum value)}$$
$$F_D \leq F_{D_{\text{max}}} \quad \text{(where } F_{D_{\text{max}}} \text{ is a predefined maximum value)}$$
$$F_A > 0 \quad \text{(ensuring a positive value for } F_A\text{)}$$
$$F_D > 0 \quad \text{(ensuring a positive value for } F_D\text{)}$$

D. Method

The optimization is performed using the COBYLA (Constrained Optimization BY Linear Approximations) algorithm. The initial guess for the optimization is set to $\beta = 0.01$ radians and $\gamma = 0$ radians.

E. Results

Upon successful optimization, the optimal values for β and γ are obtained, along with the final values of angle-dependent factors F_A and F_D. Additionally, the optimal tilt and azimuth angles are presented in degrees for practical interpretation.

The objective function value represents the total incident solar radiation on the PV modules for the optimal configuration.

IV. Dataset Selection

A. Dataset Collection and Description

The National Renewable Energy Laboratory (NREL) has compiled a solar and meteorological dataset spanning the last 3 years, with readings sampled at a 15-minute temporal resolution. Obtained from solar monitoring stations, the dataset includes measurements of global horizontal irradiance (GHI), direct normal irradiance (DNI), and diffuse horizontal irradiance (DHI), along with meteorological parameters like temperature, dew point, wind speed, and direction. Time stamps, denoting year, month, day, hour, and minute, identify each observation. NREL employs various instruments, such as pyranometers and pyrheliometers, to collect these measurements. The dataset undergoes preprocessing steps, including handling missing values and normalization. The overall data collection and storage adhere to quality control standards, enabling researchers to access this resource for solar energy analysis.

The data, obtained from the National Renewable Energy Laboratory (NREL), includes information about solar irradiance (GHI, DNI, DHI), weather conditions (Temperature, Dew Point, Relative Humidity, Wind Direction, Wind Speed, Pressure, Precipitable Water), and time stamps (Year, Month, Day, Hour, Minute). Preprocessing involved handling missing values, removing outliers, and normalizing numerical features. GHI (Global Horizontal Irradiance), DNI (Direct Normal Irradiance), and DHI (Diffuse Horizontal Irradiance) along with other features were utilized throughout the analysis to streamline the representation of solar irradiance components.

TABLE I
SALIENT FEATURES

Feature	Unit
Temperature	Degrees celsius
Clearsky DHI	(W/m^2)
Clearsky DNI	(W/m^2)
Clearsky GHI	(W/m^2)
Cloud Type	Type of Cloud (0-12)
Dew Point	Temperature (C)
DHI	(W/m^2)
DNI	(W/m^2)
GHI	(W/m^2)
Relative Humidity	-
Solar Zenith Angle	Degrees
Precipitable Water	cm
Wind Direction	Direction
Wind Speed	m/s

B. Model

The current model used the GHI, Solar Zenith Angle to find every irradiance instance on the panels both the rear and front side which is then used in the objective function to find the optimal solution.

V. SIMULATION

PVSyst software is very popular in the industry for predicting the PV output and doing economic analysis. The values find the previous section would be used to simulate the whole plant. The variable parameters in PVSyst are: Orientation - Tracking, System definition, Detailed losses, Far shadings - Horizon, Near shadings -3D construction, Tutorial, Economic evaluation.

Abbreviations used in the table

LCOE: Levelized Cost of Energy
NPV: Net Present Value
IRR: Internal Rate of Return
ROI: Return on Investment

The combined table provides a comprehensive overview of the performance metrics for different tilt angles in the PV system. Tilt angles of 32.93 degrees (reference), 25 degrees (PVSyst simulation), and 24.6 degrees (proposed) are compared based on key indicators.

TABLE II
PV SYSTEM COMPARISON - PART 1

Tilt Angle	Performance Metrics		
	LCOE (USD/KWh)	Payback Period (Years)	NPV/ USD
32.93 [13]	0.0426	6.3	383,173
25 (PVSyst)	0.0422	6.2	390,159
24.6 (Proposed)	0.0401	5.9	426,344

TABLE III
PV SYSTEM COMPARISON - PART 2

Tilt Angle	Performance Metrics		
	IRR / %	ROI / %	Energy KWh/Year
32.93 [13]	14.88	217.3	334,385
25 (PVSyst)	15.08	220.9	337,608
24.6 (Proposed)	16.23	241.4	355,701

For cost-related metrics (Table 1), the proposed tilt angle of 24.6 degrees stands out with a lower Levelized Cost of Energy (LCOE) at \$0.0401 USD/KWh, a shorter payback period of 5.9 years, and a higher Net Present Value (NPV) of \$426,344 USD. These values suggest that the proposed tilt angle offers a more cost-effective solution compared to the reference and PVSyst scenarios.

In terms of financial returns and energy production (Table 2), the proposed tilt angle continues to exhibit superiority. It boasts the highest Internal Rate of Return (IRR) at 16.23%, a remarkable Return on Investment (ROI) of 241.4%, and an annual energy production of 355,701 KWh. These figures indicate that the proposed tilt angle not only presents an attractive financial outlook but also promises a substantial energy yield.

VI. CONCLUSION

The mathematical model is sufficient for accounting for the Albedo Factor, and Direct Irradiance. This is a simplified implementation and a less computationally expensive approach to find the optimal tilt angle using the past meteorological data. This model can be improved by accounting for the elevation of the bifacial modules. Furthermore, constraints can be added which account for different scenarios like making the most energy in the winter.

VII. FORMULA SHEET

A. Irradiance Decomposition

$$I_{GHI} = I_{DNI} \cos(\theta_Z) + I_{DNI} \quad (3)$$

- DNI - Direct Normal Irradiance
- DHI - Diffuse Horizontal Irradiance
- θ_Z - Solar zenith

B. Direct irradiance

First, the Angle of Incidence (AOI) has to find between I_{DNI} and the front/rear of the solar panel.

$$\begin{aligned}\text{AOI} = \cos^{-1}\{&\cos(\theta_Z)\times\cos(\beta)+\\ &\sin(\theta_Z)\times\sin(\beta)\times\cos(\gamma_S-\gamma_M)\}\end{aligned} \tag{4}$$

$$I_{PV:Dir(Front/Rear)} = (1-R_{loss})\times\cos(\text{AOI}_{\text{(Front/Rear)}})\times \text{I}_{DNI} \tag{5}$$

For a bifacial solar module, the tilt angle β_{Rear} and azimuth angle $\gamma_{\text{M Rear}}$ of the rear side are given by:

$$\beta_{\text{Rear}} = 180^\circ - \beta_{\text{Front}} \quad \text{and} \quad \gamma_{\text{M(Rear)}} = \gamma_{\text{M(Front)}} + 180^\circ$$

where R_{Loss} is the angle-dependent reflection loss from the module surface. When considering the reflection loss (R_{loss}) for the direct beam incident on a tilted surface, it is described by the following function of the incident angle (AOI):

$$R_{\text{loss}}(\gamma) = 1 - \left[\frac{1-\exp(-\cos AOI/\text{ar})}{1-\exp(-1/\text{ar})}\right] \tag{6}$$

where ar is the angular loss coefficient. Typical values for ar in commercial crystalline silicon wafer modules range from 0.16 to 0.17 [27].

C. Diffuse irradiance

$$\begin{aligned}
I_{PV:Diff(Iso)} &= \left(1-R^{\text{Int}}_{\text{Loss}}\right)\times I_{\text{Diff (Iso)}}\times VF_{M\rightarrow Sky}\\
I_{PV:Diff(C)} &= (1-R_{\text{Loss}})\times I_{\text{Diff }(C)}\times\cos(AOI_{Cir})\\
I_{PV:Diff(H)} &= (1-R_{\text{Loss}})\times I_{\text{Diff }(H)}\times\sin(\theta_T)\\
I_{PV:Diff} &= I_{PV:Diff(Iso)} + I_{PV:Diff(C)} + I_{PV:Diff(H)}
\end{aligned} \tag{7}$$

Note that because $IDiff(Iso)$ is isotropic, rather than for one fixed angle, $R^{\text{Int}}_{\text{Loss}}$ is the integral of reflection losses over the solid-angle window of the isotropic diffuse irradiance incident to the surface (see Eqs. (6a)–(6c) in [14]) which enable us to analytically calculate the diffuse illumination on both the front and rear surfaces of solar modules. The module-to-sky view factor ($V_{M\text{Sky}}$) and the angle of incidence for circumsolar diffuse light (AOI_{Cir}) are given by:

$$V_{M\text{Sky}} = \frac{1+\cos(\theta)}{2} \tag{8}$$

$$\text{AOI}_{\text{Cir}} = \begin{cases}\text{AOI}_{\text{Direct}} & \text{if } \theta_Z \le 85^\circ\\ \text{AOI}_{\text{Diffuse}} & \text{otherwise}\end{cases} \tag{9}$$

From [14], works for(tilt angle ¡ 45):

$$\begin{aligned}
F_{\text{B}}(\alpha) =& \frac{\exp(-\cos a/a_{\text{r}})-\exp(-1/a_{\text{r}})}{1-\exp(-1/\alpha_{\text{r}})}\\
F_{\text{A}}(\beta) \cong& \exp\left[-\frac{1}{a_{\text{r}}}\left(c_1\left(\sin\beta+\frac{\beta-\sin\beta}{1-\cos\beta}\right)\right.\right.\\
&\left.\left.+c_2\left(\sin\beta+\frac{\beta-\sin\beta}{1-\cos\beta}\right)^2\right)\right] \qquad (10)\\
F_{\text{D}}(\beta) \cong& \exp\left[-\frac{1}{a_{\text{r}}}\left(c_1\left(\sin\beta+\frac{\pi-\beta-\sin\beta}{1+\cos\beta}\right)\right.\right.\\
&\left.\left.+c_2\left(\sin\beta+\frac{\pi-\beta-\sin\beta}{1+\cos\beta}\right)^2\right)\right]
\end{aligned}$$

References

[1] J. B. Jahangir, M. Al-Mahmud, M. S. S. Shakir, A. Haque, M. A. Alam, and M. R. Khan, “A Critical Analysis of Bifacial Solar Farm Configurations: Theory and Experiments,” *IEEE Access*, vol. 10, pp. 47726–47740, 2022. Conference Name: IEEE Access.

[2] S. Tsuchida, T. Tsuno, D. Sato, T. Oozeki, and N. Yamada, “Albedo-Dependent Bifacial Gain Losses in Photovoltaic Modules With Rear-Side Support Structures,” *IEEE Journal of Photovoltaics*, vol. 13, pp. 938–944, Nov. 2023. Conference Name: IEEE Journal of Photovoltaics.

[3] R. Guerrero-Lemus, R. Vega, T. Kim, A. Kimm, and L. E. Shephard, “Bifacial solar photovoltaics – A technology review,” *Renewable and Sustainable Energy Reviews*, vol. 60, pp. 1533–1549, July 2016.

[4] S. S. Kshatri, J. Dhillon, S. Mishra, R. Tariq, N. K. Sharma, M. Bajaj, A. U. Rehman, M. Shafiq, and J.-G. Choi, “Reliability analysis of bifacial pv panel-based inverters considering the effect of geographical location,” *Energies*, vol. 15, no. 1, 2022.

[5] R. O. Yakubu, M. T. Ankoh, L. D. Mensah, D. A. Quansah, and M. S. Adaramola, “Predicting the potential energy yield of bifacial solar pv systems in low-latitude region,” *Energies*, vol. 15, no. 22, 2022.

[6] A. A. Mehadi, M. M. Nishat, F. Faisal, A. R. H. Bhuiyan, M. Hussain, and M. A. Hoque, “Design, simulation and feasibility analysis of bifacial solar pv system in marine drive road, cox’s bazar,” 2021.

[7] R. Kopecek and J. Libal, “Bifacial photovoltaics 2021: Status, opportunities and challenges,” *Energies*, vol. 14, no. 8, 2021.

[8] H. F. Mueller, “Optimization of bifacial photovoltaics by optical systems feasibility study,” *Journal of Physics: Conference Series*, vol. 2548, p. 012015, jul 2023.

[9] O. A. Al-Shahri, F. B. Ismail, M. Hannan, M. H. Lipu, A. Q. Al-Shetwi, R. Begum, N. F. Al-Muhsen, and E. Soujeri, “Solar photovoltaic energy optimization methods, challenges and issues: A comprehensive review,” *Journal of Cleaner Production*, vol. 284, p. 125465, 2021.

[10] R. Dufo-López, I. R. Cristóbal-Monreal, and J. M. Yusta, “Stochastic-heuristic methodology for the optimisation of components and control variables of PV-wind-diesel-battery stand-alone systems,” *Renewable Energy*, vol. 99, pp. 919–935, Dec. 2016.

[11] Y. Zheng, B. M. Jenkins, K. Kornbluth, and C. Træholt, “Optimization under uncertainty of a biomass-integrated renewable energy microgrid with energy storage,” *Renewable Energy*, vol. 123, pp. 204–217, Aug. 2018.

[12] T. E. K. Zidane, A. S. Aziz, Y. Zahraoui, H. Kotb, K. M. AboRas, Kitmo, and Y. B. Jember, “Grid-connected solar pv power plants optimization: A review,” *IEEE Access*, vol. 11, pp. 79588–79608, 2023.

[13] X. Sun, M. R. Khan, C. Deline, and M. A. Alam, “Optimization and Performance of Bifacial Solar Modules: A Global Perspective,” *Applied Energy*, vol. 212, pp. 1601–1610, Feb. 2018. arXiv:1709.10026 [physics].

[14] N. Martin and J. Ruiz, “Calculation of the pv modules angular losses under field conditions by means of an analytical model,” *Solar Energy Materials and Solar Cells*, vol. 70, no. 1, pp. 25–38, 2001.