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Energy analysis of bifacial photovoltaic systems on different soils and orientations in a coastal low-latitude area

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ABSTRACT

Coastal low-latitude regions exhibit consistent annual solar irradiance, offering stable solar resource availability that enhances their suitability for year-round photovoltaic energy generation. This study analyzes the annual energy production of bifacial photovoltaic (PV) systems under varying ground albedo conditions and installation orientations, accounting for the effects of tilt angle, ground clearance height, ground coverage ratio (GCR), and row spacing. Meteorological parameters were derived from Japan's Himawari-8/9 satellite data, which were integrated into the System Advisor Model and the National Renewable Energy Laboratory database to compute front- and rear-side solar irradiance. Electrical measurements from bifacial PV systems were used to evaluate annual energy output and bifacial gain. Results demonstrate that landscape-oriented bifacial PV systems consistently outperformed portrait-oriented configurations in both energy production and bifacial gain. For systems with optimized parameters, landscape orientations achieved annual energy outputs 0.70%, 0.51%, and 0.42% higher than portrait orientations for white dry sands, white sands with granite rocks, and white wet sand substrates, respectively. Similarly, bifacial gain values for landscape-oriented systems reached 18.64%, 15.47%, and 12.43% across these substrates, surpassing portrait-oriented systems. The findings highlight the crucial influence of ground albedo and panel orientation on optimizing the performance of bifacial photovoltaic systems in coastal low-latitude regions.

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1. INTRODUCTION

Bifacial photovoltaic (PV) technology has received growing attention in recent years owing to its capacity to generate higher energy yields than conventional monofacial systems. By capturing direct irradiance on the front surface and reflected light on the rear, bifacial panels can achieve up to 30% greater energy output than their monofacial counterparts [1], [2]. As bifacial PV technology matures and costs continue to decline, the deployment of these systems is projected to accelerate, positioning them as main contributors to the global transition to renewable energy.

The performance of bifacial PV systems varies significantly depending on geographic locations, environmental conditions, and installation parameters. Key factors influencing their energy output include surface reflectivity (albedo), solar irradiance, ambient temperature, tilt angle, orientation, and mounting height above the ground. An analytical model considering albedo, tilt angle, orientation, panel height, and row spacing was developed to evaluate a bifacial PV system in Detroit, United States [3]. The study found that the bifacial system produced approximately 31% more energy than its monofacial counterpart, highlighting the benefits of optimizing these parameters. Another study at Vellore Institute of Technology examined a rooftop bifacial PV system and found that a 30° tilt angle optimized energy generation by capturing direct sunlight and reflected light from a white surface, yielding the highest average daily power output [4]. This configuration successfully leveraged albedo effects and ideal tilt to maximize bifacial gains in Vellore conditions.

The orientation and tilt angles of bifacial PV systems significantly influence their energy yield. In desert environments (characterized by high soiling rates and elevated ground albedo), tilted installations with solar tracking and vertically mounted bifacial PV systems optimize energy capture and improve return on investment [5], [6]. In this case, solar tracking enhances energy generation by maximizing irradiance exposure on both panel surfaces. Meanwhile, vertical installations offer distinct advantages for mitigating soiling losses while sustaining energy output. Another related study [7] also demonstrated that vertical bifacial configurations reduced soiling-induced performance degradation by 9.2% and surpassed inclined installations under specific conditions.

Bifacial PV systems are better than monofacial configurations in snowy environments owing to enhanced snow-shedding capabilities [8]. A study under Canadian climatic conditions [9] revealed that front-surface snow coverage reduced energy yield by up to 80%, rendering the rear surface the exclusive contributor to power generation during such events. Vertical installations further improve resilience by minimizing snow accumulation and reducing structural risks from substantial snow loads. Additionally, an optimized installation strategy addressing snow shading effects [10] resulted in an increase in bifacial PV energy generation of up to 4.3%.

In agricultural settings, bifacial PV systems integrated with agrivoltaic practices enable synergistic dual land use for concurrent energy generation and crop production, enhancing resource efficiency [11]. These systems increase energy yields while promoting sustainable agriculture. A study on UK potato farmlands [12] found that system configurations and geographic locations significantly influenced the agrivoltaic performance. Similarly, another study in Boston, United States [13], showed that bifacial PV arrays in agrivoltaic applications boosted electricity generation and land productivity. Similar to agricultural environments, grasslands (characterized as open-canopy ecosystems with herbaceous vegetation, minimal tree cover, and high solar exposure) also offer favorable conditions for bifacial PV deployment due to high irradiance availability and moderate ground albedo. However, optimal energy yield is typically achieved through tilted installations or elevated mounting to maximize rear-side irradiance capture [14].

Coastal environments exhibit distinct albedo characteristics relative to high-reflectivity zones such as deserts or snow-covered areas. Although coastal albedo values are generally lower, these regions present unique conditions due to the dynamic interplay between sand and water substrates. Sandy surfaces generally have moderate albedo (0.3-0.4), exceeding grassland reflectance but remaining substantially below snow albedo [15]. Notably, dry sand albedo remains stable across solar elevation angles but is sensitive to moisture content [16]. Conversely, water reflectance varies significantly with solar altitude: low angles (e.g., sunrise/sunset) intensify specular reflection [17], potentially enhancing rear-side irradiance in bifacial PV systems. Coastal regions further benefit from elevated wind speeds, which enhance convective panel cooling. This gives a critical factor for PV operating temperature. Furthermore, installation parameters require careful optimization. The elevated mounting mitigates sand accumulation and facilitates passive cooling via airflow, while tilt angle adjustments exploit water-surface reflections to maximize energy yield in near-shore deployments. Additionally, bifacial PV systems in humid coastal zones capitalize on diffuse irradiance from atmospheric moisture scattering. This phenomenon enables consistent light capture on both panel surfaces under overcast conditions, and hence promoting more stable energy output compared to clear-sky-dominated arid regions.

Existing studies on bifacial PV systems predominantly focused on mid-latitude regions (15°-40° N/S), with limited investigations addressing installations below 5° latitude. In addition, previous studies have not conducted a systematic evaluation of the effect of panel orientation on the performance of bifacial PV systems. This study investigated the energy yield potential of bifacial PV systems under varying ground albedo conditions at a low-latitude coastal site. The selected location was a coastal area in Temajuk, Indonesia (2.0558° N, 109.6251° E). Critical parameters, including azimuth, solar irradiance, ambient temperature, and bifaciality coefficient, were taken into account to ensure precision. Three coastal sites representing distinct albedo conditions were evaluated: i) dry white sands, ii) wet white sands, and iii) white sands dotted with granite rocks. Annual energy output and bifacial gain were comprehensively analyzed across both panel orientations, examining the effects of tilt angle (0°-30°), ground clearance (0.1-3.0 m), and ground coverage ratio (GCR; varied via row spacing and pitch) under site-specific albedo conditions.

2. METHOD

2.1. Solar radiation

Figure 1 shows the monthly average daily solar radiation components obtained from the Japan Meteorological Agency's Himawari satellite. These datasets, characterized by high spatial and temporal resolution (60-minute intervals), were validated against ground-based measurements to ensure accuracy. The validated data were subsequently integrated into the system advisor model (SAM) for simulating and analyzing renewable energy systems. In this study, these solar radiation parameters are used to assess system performance and energy output for bifacial PV installations.

As shown in Figure 1, the direct normal irradiance (DNI) peaks during April-July, with maximum intensity observed in June due to the solar zenith angle reaching its annual minimum. The diffuse horizontal irradiance (DHI) exhibits its highest values during February and March under overcast skies, where cloud cover enhances light dispersion. Conversely, the DHI diminishes under clear-sky conditions due to reduced scattering. A notable inverse relationship exists between the DNI and the DHI. During solar noon in June and July, when the DNI is maximal, the DHI reaches its nadir as minimal scattering occurs. The global horizontal irradiance (GHI), representing the total incident solar radiation, achieves its maximum in March and April under clear skies. The lowest GHI values occur from November to February due to persistent cloud cover attenuating incoming solar radiation. Finally, the annual average irradiances for DNI, DHI, and GHI are 2.87, 2.82, and 4.80 kWh/m^2/day, respectively, with an accompanying annual mean ambient temperature of 27.4 °C. These patterns underscore the interdependence of solar radiation components and local climatic conditions.

2.2. System configuration

The bifacial PV system comprises two bifacial panels installed as illustrated in Figure 2. Each panel measures 2.096 m in length and 1.212 m in width, with detailed parameters provided in Table 1. The PV panels are mounted at a tilt angle (β) and oriented southward to maximize solar radiation exposure. The system is defined by a ground clearance height (H), row spacing (D), and row-to-row pitch (R). The panel length perpendicular to the row direction is denoted as L.

2.3. Mathematical model

A bifacial PV model simulates the energy production of bifacial solar panels by considering front- and rear-side irradiance and by integrating environmental parameters to predict system performance. The model computes the total solar irradiance on each side: front-side irradiance comprises direct, diffuse, and reflected components, while rear-side irradiance consists of diffuse and ground-reflected light, as seen in Figure 2.

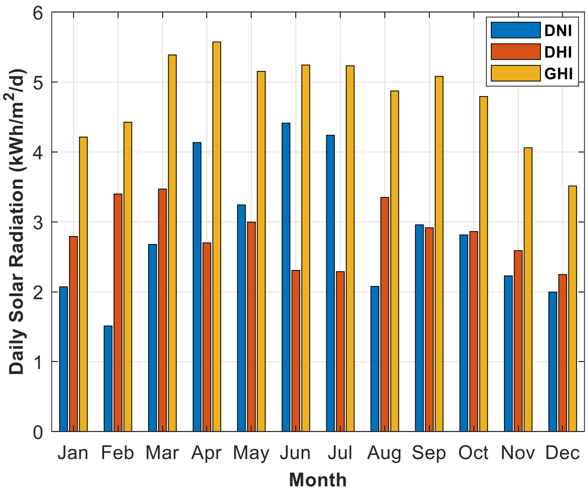


Figure 1. Solar radiation data

Table 1. Bifacial PV data

Parameters	Value
Maximum power (P_{MP})	520 W
Temperature coefficient of power (γ)	-0.374%/°C
Panel efficiency (η_{MPP})	20.47%
Nominal operating cell temperature ($T_{c,NOCT}$)	45.9 °C
Bifaciality factor (φ)	0.7

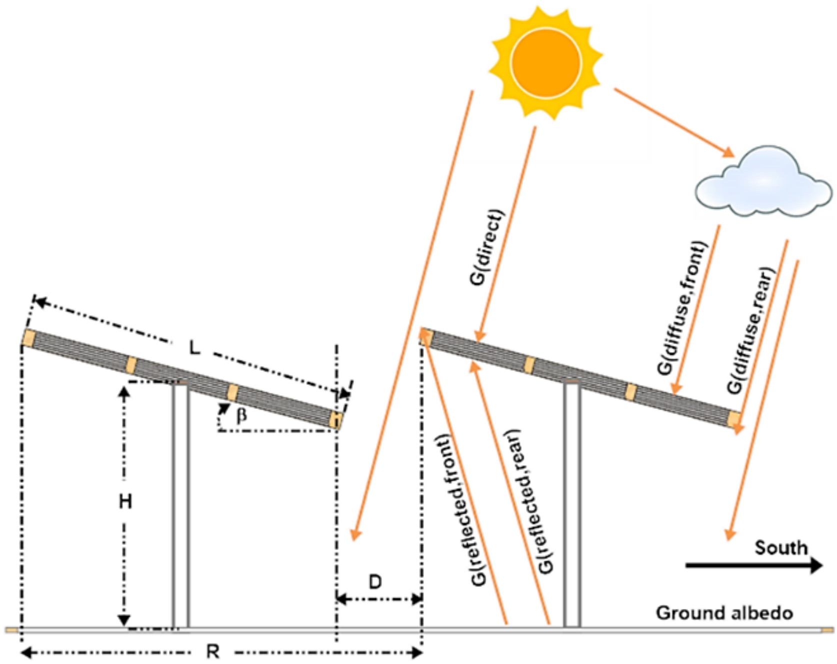


Figure 2. Bifacial PV system configuration

The front-side irradiance (G_{front}), including direct, diffuse, and ground-reflected components, is calculated by (1).

$$G_{front} = G_{direct} + G_{diffuse,front} + G_{reflected,front} \quad (1)$$

The direct beam irradiance (G_{direct}) can be calculated with (2).

$$G_{direct} = DNI.\cos(\theta) \quad (2)$$

Here, θ represents the solar zenith angle and *DNI* is the direct normal irradiance, i.e., the solar radiation arriving directly from the sun; the condition $\theta < 90°$ must be satisfied [18]. Adopting the isotropic sky diffuse model [19], the front-side diffuse sky irradiance $G_{diffuse,front}$ is given by (3).

$$G_{diffuse,front} = DHI.\frac{1+\cos(\beta)}{2} \quad (3)$$

Where β represents the tilt angle of the PV panel measured from the horizontal, and *DHI* denotes the diffuse horizontal irradiance, defined as the solar radiation scattered by the atmosphere that is incident on a horizontal surface from all directions. The front-side ground-reflected irradiance is calculated as (4).

$$G_{reflected,front} = GHI.\rho_g.\frac{1-\cos(\beta)}{2} \quad (4)$$

Where ρ_g denotes the ground albedo, and *GHI* is the global horizontal irradiance, defined as the total solar radiation from both direct and diffuse components, received on a horizontal surface. The rear-side irradiance G_{rear} consists of diffuse and ground-reflected components that depend primarily on light reflected from the ground and surrounding surfaces, as (5).

$$G_{rear} = G_{diffuse,rear} + G_{reflected,rear} \quad (5)$$

The rear diffuse sky irradiance ($G_{diffuse,rear}$) is (6).

$$G_{diffuse,rear} = DHI.\frac{1-\cos(\beta)}{2} \quad (6)$$

The rear ground-reflected irradiance is given by (7).

$$G_{reflected,rear} = GHI.\rho_g.\frac{1+\cos(\beta)}{2}.F_{view} \tag{7}$$

The view factor (F_{view}) is the fraction of ground visible to the rear side [20], as (8).

$$F_{view} = \frac{1}{2}.(1+cos(\beta)).\left(1-\frac{D}{\sqrt{D^2+H^2}}\right) \tag{8}$$

Where β, H and D is the PV panel tilt angle, ground clearance height and row spacing, respectively. Finally, the total effective irradiance (G_{total}) contributed by front-side and rear-side irradiances is written as (9).

$$G_{total} = G_{front} + \varphi.G_{rear} \tag{9}$$

Where φ is the bifaciality factor, a metric that quantifies the power generation capacity of the rear surface of a bifacial PV panel relative to its front side under identical irradiance. The power output of the bifacial PV system is then calculated using the following relation [21]:

$$P_{PV} = P_{MP}.\frac{G_{total}}{G_{STC}}.\eta_{MPP}.\left(1+\gamma.\left(T_c - T_{c,STC}\right)\right).\left(1+D_f\right) \tag{10}$$

Here, P_{MP} is the maximum power at standard test conditions (STC); η_{MPP} is the panel efficiency at the maximum power point under STC; G_{STC} = 1000 W/m^2 is the reference irradiance at STC; γ is the temperature coefficient of power (expressed in %/°C); $T_{c,STC}$ = 25 °C is the cell temperature at STC; T_c is the cell temperature under operating conditions (°C); and D_f is the dimensionless derating factor, which accounts for rear-side irradiance losses caused by racking or obstructions. The T_c is typically higher than the T_a and can be estimated as (11).

$$T_c = T_a + \frac{G_{total}}{G_{NOCT}}.\left(T_{c,NOCT} - T_{a,NOCT}\right) \tag{11}$$

Where T_a is the ambient temperature under operating conditions (°C); $T_{c,NOCT}$ is the cell temperature at which the nominal operating cell temperature (NOCT) is specified (°C); $T_{a,NOCT}$ = 20 °C is the ambient temperature under NOCT; and G_{NOCT} = 800 W/m^2 is the irradiance at NOCT. The parameters η_{MPP}, γ, and $T_{c,NOCT}$ are typically provided by the manufacturer in the panel datasheet.

3. RESULTS AND DISCUSSION

This study evaluates the performance of bifacial PV systems at three coastal sites in Temajuk, Indonesia, each distinguished by unique surface albedo conditions: white dry sands, white wet sands, and white sands interspersed with granite rock inclusions. The measured albedo values for these surfaces are 0.36 for white dry sands, 0.30 for white sands with granite rock inclusions, and 0.24 for white wet sands. The orientation of PV panels significantly influences energy production [22]; therefore, the installation orientations (portrait and landscape) are considered. In the portrait orientation, the panels are mounted with their short side parallel to the ground, whereas in the landscape orientation, the long side is aligned parallel to the ground (as seen in Figure 3).

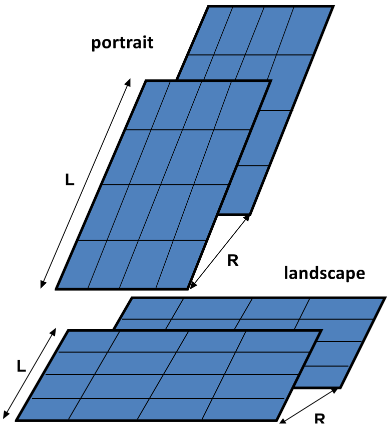


Figure 3. PV panel orientations

3.1. Influence of tilt angle

Figure 4 demonstrates the influence of tilt angle on the annual electrical energy of the bifacial PV system, accounting for site-specific albedo and panel orientation. Optimal system performance is achieved at a low tilt angle with a south-facing orientation, a configuration that maximizes solar irradiance capture in low-latitude regions of the northern hemisphere [23]. As depicted in Figure 4, the landscape-oriented bifacial PV system achieves higher energy productions compared to the portrait-oriented configuration under identical tilt angle and albedo conditions. This performance disparity arises primarily from geometric and irradiance distribution effects. The reduced vertical profile of landscape-oriented panels mitigates self-shading phenomena on the rear surface, whereas the taller aspect ratio of portrait configuration induces mutual shading between adjacent panels, particularly at low tilt angles. Such shading diminishes incident irradiance on rear-side cells, hence reducing effective energy generation. In contrast, the landscape orientation preserves uniform rear-side illumination by minimizing inter-panel obstruction. Furthermore, the tilt-induced vertical height reduction in the landscape configuration positions the rear surface closer to the ground, thereby augmenting the view factor [20]. This proximity enhances the PV panels to harness reflected light. Collectively, these geometric advantages in shading avoidance and optimized angular reception of diffuse and reflected light contribute to the observed energy output superiority of the landscape-oriented bifacial PV system.

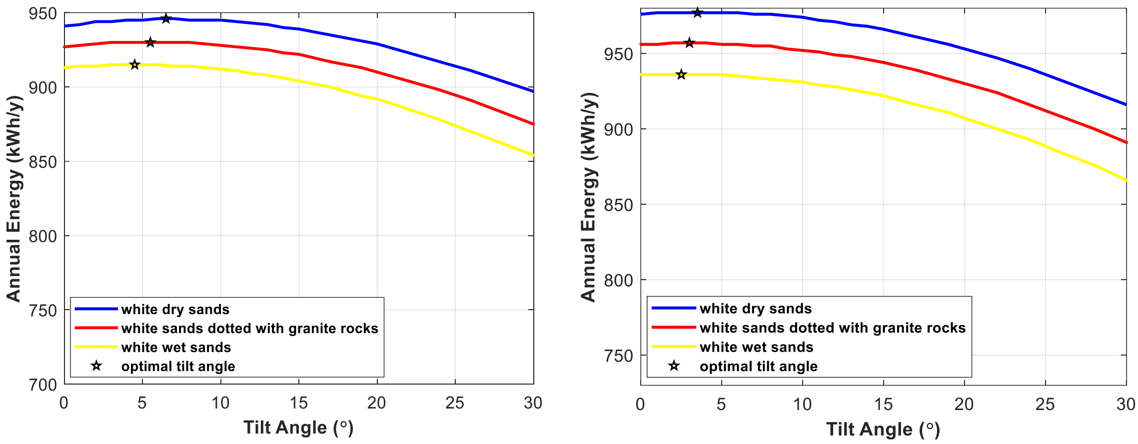


Figure 4. Variations of annual energy with tilt angle: (a) portrait orientation and (b) landscape orientation

While both orientations achieve optimal performance at low tilt angles, the landscape configuration attains a lower optimal tilt angle than the portrait configuration. Higher tilt angles orient the panels away from the solar zenith, thereby reducing front-side irradiance capture. At low latitudes, the small solar zenith angle causes ground-reflected irradiance to strike the rear surface at shallow incidence angles; the landscape arrangement is therefore more favorably aligned to intercept these reflections. Conversely, the portrait orientation exhibits limited rear-side exposure at low tilts because the rear cells are positioned closer to the ground and may be shaded by adjacent rows.

Albedo plays a critical role in enhancing the total irradiance incident on tilted surfaces. As illustrated in Figure 4, the annual optimal tilt angle exhibits a positive correlation with albedo for both landscape- and portrait-oriented bifacial PV systems. For the landscape-oriented configuration, the optimal tilt angle increases from 2.5° to 3.5° as albedo rises from 0.24 to 0.36. Similarly, for the portrait-oriented configuration, the optimal tilt angle increases from 4.5° to 6.5° over the same albedo range. Furthermore, computational analysis demonstrates that the landscape-oriented bifacial PV system achieves annual energy output enhancements of 2.3%, 2.9%, and 3.3% relative to the portrait-oriented configuration under albedo conditions of 0.24, 0.30, and 0.36, respectively, when tilt angles are independently optimized for each orientation. This trend arises because elevated albedo amplifies annual ground-reflected irradiance, thereby increasing total incident solar radiation [24]. Additionally, the bifacial PV system receives greater total incident solar radiation in the landscape-oriented configuration compared to the portrait-oriented one under optimal tilt angles and identical albedo conditions.

3.2. Influence of ground clearance height

The effect of ground clearance height on the performance of bifacial PV systems was investigated by varying the height and ground albedo while keeping all other parameters at their optimized values. The rear-side energy yield exhibits a strong dependence on both clearance height and albedo, with maximum output achieved under high-albedo surfaces combined with elevated mounting [25]. Figure 5 illustrates the relationship between clearance height and annual energy yield for the site-specific albedo conditions and panel orientations considered. Energy output initially increases with height due to enhanced view factor expansion, which enlarges the effective ground area contributing to reflected irradiance capture. Beyond a critical height threshold, however, energy gain plateaus, indicating saturation where further elevation yields diminishing returns. This trend aligns with the maximized rear-side field of view for irradiance collection at greater heights.

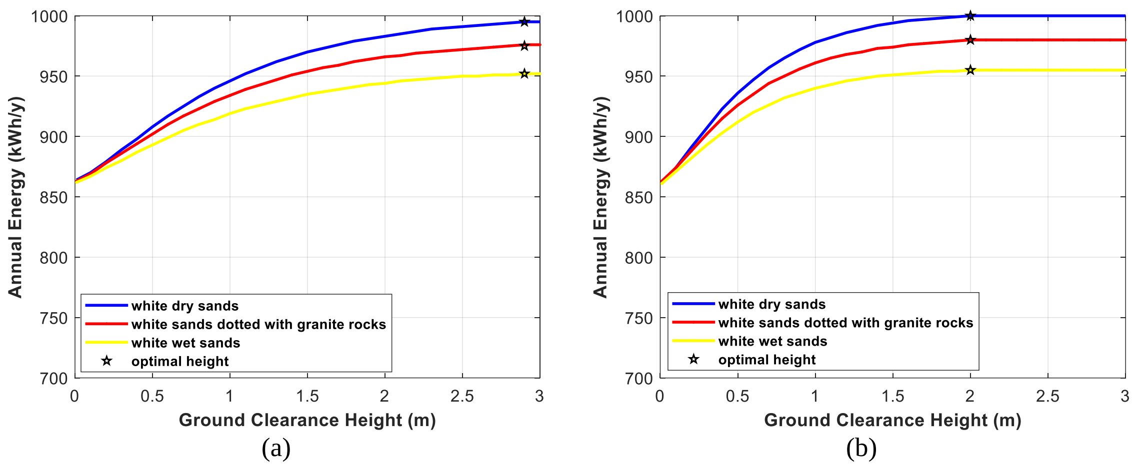


Figure 5. Variations of annual energy with ground clearance height: (a) portrait orientation and (b) landscape orientation

The optimal ground clearance height for the bifacial PV system corresponds to the point beyond which no significant energy gain is observed, as illustrated in Figure 5. For the bifacial PV system in landscape orientation, energy output increases measurably with mounting heights up to 1.5-2.0 m across all albedo conditions. Elevating the system from 0.5 m to 2.0 m enhances energy output by 4.7-6.8%, contingent on surface albedo. Empirical studies [13], [26] identify 2.0 m as the optimal height for maximizing annual performance in landscape configurations, balancing rear-side irradiance capture and diminishing returns at greater elevations.

Similarly, for portrait-oriented systems, energy output improves with ground clearance heights up to 2.5-2.9 m, irrespective of albedo. Raising the height from 0.5 m to 2.9 m similarly amplifies energy output by 6.6-9.6%, with 2.9 m achieving optimal annual performance. This height-dependent response aligns with field observations [26], where increased elevation expands the rear-side field of view for reflected irradiance. However, it should be noted that increasing the mounting height to 2.9 m would result in elevated wind loads on the PV panels, necessitating a reinforced substructure to ensure stability. Consequently, the deployment of portrait-oriented bifacial PV systems in coastal regions is not recommended due to these heightened structural and environmental challenges.

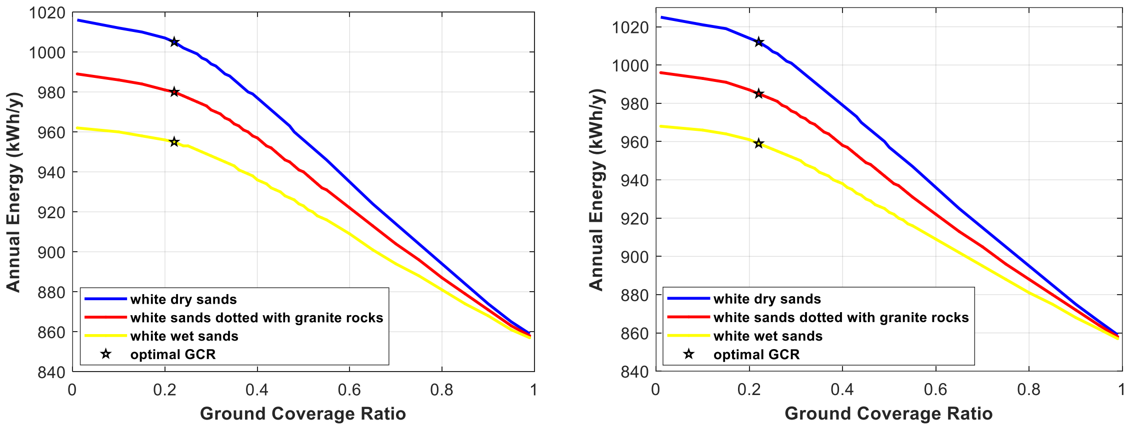
The landscape orientation demonstrates superior performance to the portrait orientation in the bifacial PV system operating at equivalent ground clearance heights. This preference arises from the landscape configuration's ability to mitigate vertical irradiance gradients across the panel surface, ensuring more uniform distribution of ground-reflected light along the panel width. Furthermore, the horizontal alignment of landscape-oriented panels enlarges the rear-side field of view, enhancing the effective albedo capture by integrating a greater proportion of diffuse and specular reflections from the ground and surrounding surfaces. Such optimization of rear-side irradiance uniformity and albedo utilization maximizes bifacial energy gain.

Elevated ground clearance height exerts a more pronounced effect on bifacial PV energy yield in high-albedo configurations. Systems with high-albedo surfaces achieve significantly greater energy production than low-albedo counterparts [27], underscoring the importance of albedo in contributing to height-dependent performance gains. Computational simulations confirm these findings: landscape-oriented systems exhibit annual yield enhancements of 0.3%, 0.4%, and 0.5% relative to portrait orientation at albedo values of 0.24, 0.30, and 0.36 respectively, when clearance height is independently optimized per orientation.

3.3. Influence of ground coverage ratio

The ground coverage ratio (GCR), a vital design parameter in a bifacial PV system. It represents the ratio of the total PV panel area to the occupied ground area. For the bifacial PV system, which harness rear-side irradiance from reflected and diffuse light, GCR optimization directly influences energy output by balancing inter-row shading losses and albedo-driven gains. The GCR for bifacial PV system is mathematically expressed as the ratio of the panel length (L) to the row-to-row pitch (R) (i.e., GCR = L/R). A lower GCR corresponds to greater inter-row spacing (R), which reduces mutual shading but increases land use, while a higher GCR intensifies shading effects, thereby limiting rear-side illumination.

Figure 6 illustrates the effect of varying the GCR on the annual electrical energy output of the bifacial PV system, accounting for site-specific albedo conditions and PV panel orientations, while holding all other system parameters constant at their optimized values. The bifacial PV system with a lower GCR features a larger row spacing (D) than those with a higher GCR. A reduced GCR increases the available ground area, thereby enhancing albedo-driven irradiance reflection onto the rear surfaces of the PV panels. This effect is particularly pronounced under higher albedo conditions, where increased ground reflectance amplifies rear-side irradiance gains, as demonstrated by the comparative data in Figure 5. Conversely, higher GCR values diminish annual energy output due to inter-row shading losses, as intensified mutual shading between adjacent PV arrays restricts incident light reaching the rear-side of the panels [28]. Additionally, a GCR below 0.5 optimizes rear-side exposure to diffuse and reflected radiation, aligning with findings from existing studies on bifacial PV performance under varying ground cover conditions [29].



(a) (b)

Figure 6. Variations of annual energy with GCR: (a) portrait orientation and (b) landscape orientation

This study identifies an optimal GCR of 0.22 for the bifacial PV system, irrespective of PV panel orientations (portrait or landscape). This finding aligns closely with prior research [30], which proposed a GCR of 0.2 to maximize both energy generation and economic returns. Nonetheless, across all albedo conditions, the landscape-oriented configuration exhibits a consistently higher energy output than the portrait-oriented system when both are optimized to their respective GCR values. Specifically, the landscape orientation achieves optimal performance with a row spacing of 4.3 m, whereas the portrait orientation requires a wider spacing of 7.5 m to mitigate inter-row shading losses. The reduced spacing requirement for landscape-oriented panels is attributed to their shorter panel length, which minimizes rear-side shading while maintaining a lower GCR.

The analysis reveals a marked progressive decline in annual energy output as the GCR increases for bifacial PV systems. Specifically, raising the GCR from 0.10 to 0.22 reduces annual energy output by 0.69%, while further increments from 0.22 to 0.30 and 0.30 to 0.40 result in reductions of 1.10% and 1.71%, respectively. Notably, increasing the GCR from 0.22 to 0.50 leads to a significant annual energy loss of 5.43%, highlighting a nonlinear relationship between GCR and energy performance in bifacial PV systems. This nonlinearity suggests that shading and rear-side irradiance losses intensify disproportionately at higher GCR values. A study on the economics and energy of bifacial PV systems [31] showed that both energy yield and economic benefits decrease with increasing GCR, and the marginal reduction becomes less pronounced in high GCR regimes (e.g., GCR >0.30).

3.4. Bifacial gain

Bifacial gain is a performance metric defined as the percentage increase in effective irradiance (and thus energy production) of bifacial PV systems compared to monofacial counterparts, accounting both plane of array (POA) front irradiance and POA rear irradiance, adjusted by bifaciality factor (φ). This gain is attributed to the capacity of bifacial PV panels to harness irradiance incident on both the front and rear surfaces, thereby augmenting total energy yield. This metric is pivotal for evaluating the energy advantages of bifacial technology, as it quantifies the synergistic effects of albedo, system geometry, and site-specific irradiance conditions.

As delineated in Table 2, critical design parameters, including site albedo, GCR, tilt angle, ground coverage height, and row spacing. For configurations optimized with a bifaciality factor of 0.7, the portrait-oriented PV bifacial system exhibits higher POA front irradiance than the landscape-oriented system, as illustrated by data from three representative days in Figure 7. Conversely, the landscape-oriented configuration achieves greater POA rear irradiance. Despite these transient differences, the annual bifacial gain for the landscape-oriented system (18.64%) slightly exceeds that of the portrait-oriented system (18.23%), suggesting a marginal long-term performance advantage for the landscape orientation. This disparity arises from the landscape orientation reduced inter-row shading and enhanced rear-side irradiance capture, attributable to its shorter PV panel length and lower row spacing requirements. These findings align with prior studies in low-latitude regions [32], which report bifacial gains ranging from 10% to 30%, contingent on site-specific variables such as ground albedo, installation height, and shading effects. The observed gains in this study fall within this range, further validating the interplay between design optimization and environmental factors in coastal tropical environments.

Table 2. Optimal configurations

Parameters	Portrait-oriented	Landscape-oriented
Azimuth	South (180°)	South (180°)
Ground albedo (ρ_g)	White dry sands (0.36)	White dry sands (0.36)
Tilt angle (β)	6.5°	3.5°
Ground clearance height (H)	2.9 m	2.0 m
GCR	0.22	0.22
Row spacing (D)	7.5 m	4.3 m

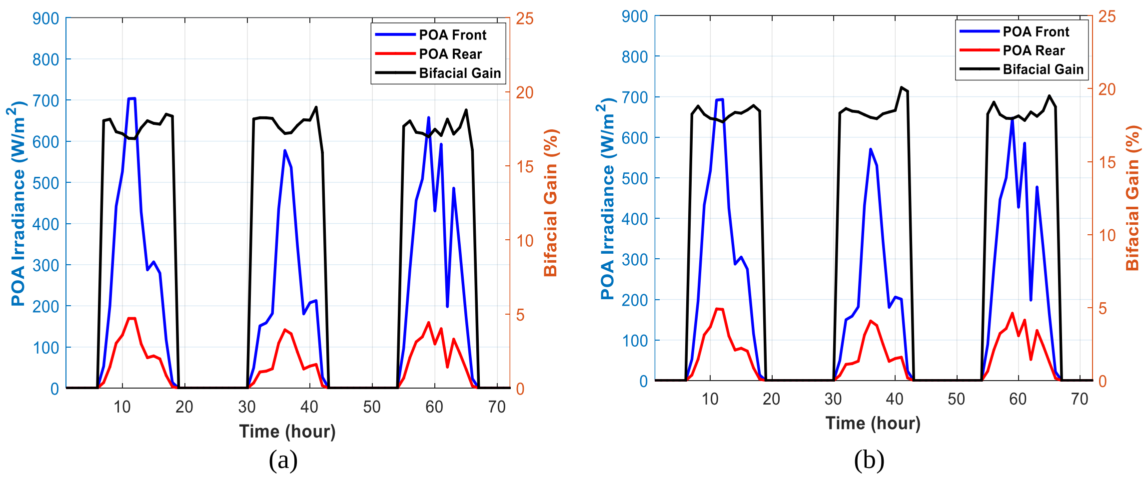


Figure 7. POA irradiance and bifacial gain: (a) portrait orientation and (b) landscape orientation

4. CONCLUSION

This study evaluates the performance of bifacial photovoltaic systems under varying soil conditions and installation orientations in a near-equatorial coastal region of Temajuk, Indonesia. By analyzing annual energy output and bifacial gain, this work demonstrates the potential of bifacial PV technology to improve solar energy generation in low-latitude coastal zones. The findings reveal that optimal bifacial PV configurations in such regions are highly sensitive to soil conditions and installation orientations. Critical design parameters, such as tilt angle, ground clearance height, GCR, and row spacing, also affect annual energy production and bifacial gain. Under optimized parameters and the highest albedo substrates (white dry sands), landscape-oriented bifacial PV systems exhibited a 0.70% higher annual energy output and an 18.64% bifacial gain compared to portrait-oriented systems. The disparity is explained by the landscape orientation's improved rear-side irradiance capture and reduced inter-row shading, which are direct consequences of its shorter panel length and the associated decrease in row spacing requirements. These results confirm the superiority of landscape orientation for bifacial PV installations in low-latitude coastal environments. These findings align with global trends in bifacial PV optimization but emphasize the critical influence of microclimatic factors in tropical coastal regions. However, the model utilized in this investigation possesses inherent limitations. To enhance the robustness of future findings, the application of uncertainty analysis is essential. This approach facilitates more reliable performance forecasting and reduces the financial exposure of bifacial PV system design.

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AUTHOR CONTRIBUTIONS STATEMENT

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C : **C**onceptualization
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I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

Authors state no conflict of interest.

DATA AVAILABILITY

The data that support the findings of this study are available from the corresponding author, [AH], upon reasonable request.

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