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Article

Modeling of energy gain in bifacial vertical PV fences

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Abstract: A quantitative model-based analysis was conducted to estimate the percentage output energy ratio of vertically installed bifacial PV modules in fences, cattle barriers, and roadsides compared to the output energy of two types of monofacial PV installations. The first comparison is between the output of the vertical bifacial PV fence and the output of the same fence furnished with vertically installed monofacial PV modules. The second comparison is between the output of the vertical bifacial fence and the output of south-facing monofacial PV modules installed at the optimal inclination angle for the particular latitude. The results show that bifacial fences can produce net yearly energy outputs up to 80% higher than those of monofacial PV modules. Additionally, vertical bifacial PV fences produce only a few percent lower energy compared to optimally installed monofacial PV modules. A MATLAB software program was written to calculate the gain of fences of any geometry, and it has been made freely available. Examples of gain results for a few such geometries are presented.

Keywords: PV-panels; PV fences; vertical installation; fences PV energy

1. Introduction

It has been almost two centuries now since Edmond Becquerel (1839) [1] demonstrated that electricity can be generated when light fall on certain materials. Over these two centuries research and developments have resulted in increases of solar cells efficiencies from less than 1% to current values of 15%–20% [2], depending on type and structure. This represents an average annual increase of about 0.1%. Photovoltaic (PV) electricity is expected to become a major player in global efforts to replace fossil fuels and address climate change. In 2023, solar PV alone accounted for three-quarters of renewable capacity additions worldwide [3]. The global capacity of PV-generated electricity has grown remarkably from around 100 GW in 2012 to over 1180 GW in 2023, an increase of 7.3% from 1110 GW at the end of 2022 [4,5].

Driven by the strong demand for increased PV efficiency, extensive research in recent decades has focused on developing new PV structures, materials, and configurations to enhance efficiency. Among various innovations, a significant development is the invention of bifacial PV panels. These panels can convert incident solar radiation to electricity on both sides. One side converts direct, diffuse, and surrounding reflected radiation, while the other side converts the latter two, which can contribute 5%–30% of the total radiation depending on the surroundings. This can result in up to a 30% increase in overall efficiency compared to mono-facial PV panels [6–10].

Although most references suggest that the introduction of bifacial PV modules was by a Spanish company called, ISO-FOTON in 1983–1984 [11,12], other references state that the first prototype bifacial PV's was introduced in 1966, and they were used by the Russians to power their satellites as early as 1970 [13]. Regardless of their history, bifacial PV modules now form a significant and rapidly growing share of the PV market. Their market share has increased from about 15% in 2019 to approximately 50% in 2024 and is expected to reach around 70% by 2030 [14].

The standard orientation for installing both monofacial and bifacial PV panels is south-facing in the northern hemisphere and north-facing in the southern hemisphere, with an appropriate inclination angle. The inclination angle depends on the latitude and the season for optimal performance [15]. Two important developments related to bifacial PV's are worth mentioning. The first is that the current market trends showing bifacial prices not significantly higher than monofacial ones. The second is that bifacial panels of bifaciality value defined as the ratio of light to electricity efficiency of the back to front side exceeding 90% are becoming more widespread. Several studies have demonstrated that choosing bifacial PV panels over monofacial ones can be economically advantageous [16,17].

The original intention of bifacial PV modules was to harvest indirect diffused and albedo-reflected radiation, both of which are almost isotropic. Additionally, the south-facing geometry ensured maximum harvesting of direct radiation. Consequently, south-facing inclined installations represent the main type application of bifacial PV modules, similar to mono-facial PV installations. However, bifacial PV modules also enjoy great directional flexibility without much reduction in their overall efficiency. This makes them ideal for situations where vertical rather than optimum inclination installation is necessary. Such situations include vertical farm fences, highway noise barriers, animal-retarding fences, and installations where horizontal solar collecting land is scarce. Such installations make good use of these fences for energy generation alongside their original designed purpose.

Most published works on bifacial solar fencing are experimental and focus on the net energy output at specific locations. To our knowledge, there are no comprehensive generalized modeling studies on this subject. Our aim is to present modeling results that compare the annual energy outputs from bifacial and mono-facial PV systems as functions of latitude and albedo value. These results will be instrumental in deciding whether to install bifacial or mono-facial solar fences at any global position.

2. Review of phenomenological basic model

The modeling used here is based on equations developed by Issaq et al. [15], which estimate the monthly, seasonal and annual optimum inclination angle for a mono-facial PV panel against latitude angle. All solar radiation models use the same geometrical equations to describe angular distribution of direct solar radiation. This direct radiation is a function of the diffusion fraction (K_d), which is in turn a function of the sky clearness factor (K_c). Most published calculations of optimum tilt angle involve setting K_c as a constant which represents the mean sky clearness factor at a particular location. The current model empirically parametrizes the experimentally measured global sky clearness factor data published by HOMER [18] in terms of both latitude angle (φ) and day of the year (n). The parametrization which also involves a random variations term (R) to account for the daily weather fluctuations is carried out using the MATLAB nonlinear fitting facility which has a 95% minimum confidence level by default. The K_c data and their two parametrizations are presented in **Figure 1**.

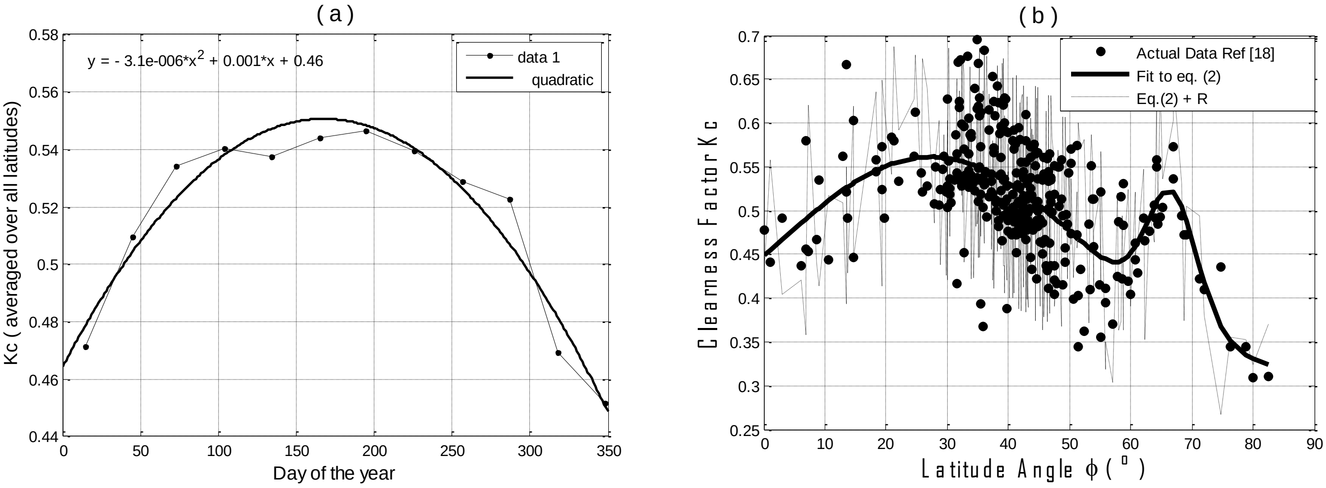

Figure 1. Empirical parametrization of sky clearness factor in terms of **(a)** time of the year; **(b)** latitude position.

The overall normalized parametrization equation of K_c obtained was:

$$K_c(n,\varphi) = 1.8182 \times [-3.1 \times 10^{-6} \times n^2 + 0.001 \times n + 0.46] \times \left[a_1 e^{-a_2(\varphi-a_3)^2} + a_4 e^{-a_5(\varphi-a_6)^2} + a_7 + R\right] \quad (1)$$

R represents a set of daily random values $-0.18 \leq R \leq 0.18$, and a_1 = 0.2632, a_2 = 0.0008, a_3 = 27.3063, a_4 = 0.1420, a_5 = 0.0302, a_6 = 66.7598, a_7 = 0.2982. Values of K_c obtained from Equation (1) are used to calculated the diffusion factor (K_d) at any latitude φ on any particular day of the year n, using the following relations [19]

$$For\ K_c < 0.35: \quad K_d = 1 - 0.249K_c \quad (2)$$

$$For\ 0.35 \leq K_c \leq 0.75: \quad K_d = 1.577 - 1.84K_c \quad (3)$$

$$For\ K_c > 0.75: \quad K_d = 0.177 \quad (4)$$

The model calculates the metric representing the effective total sunlight exposure hours $X(\varphi,\theta)$. This metric is proportional to the total sunlight radiation received by a unit area surface, facing south, positioned at latitude φ, and installed at an inclination angle θ with the horizontal, over a period between (n_1) and (n_2) days of the year. This metric is given as:

$$X(\varphi,\theta) = \sum_{n_2}^{n_1} \left\{D(n,\varphi) + [K_c(n,\varphi) - K_d(n,\varphi)] \times L(n,\varphi) \times [\cos(\varphi - \delta_n - \theta) + \left(\frac{\rho}{2}\right) \times (1 - \cos(\theta))]\right\} \quad (5)$$

The first term on the right-hand side of Equation (5) represents the diffusion part of the solar radiation defined as:

$$D(n,\varphi) = K_d(n,\varphi) \times K_c(n,\varphi) \times L(n,\varphi) \quad (6)$$

$L(n,\varphi)$, is the extraterrestrial direct radiation [20]

$$L(n,\varphi) = \frac{2}{15}\left[\frac{sin(-0.83^o) - sin\,(\varphi) \times sin\,(\delta_n)}{cos\,(\varphi) \times cos\,(\delta_n)}\right] \quad (7)$$

$$\delta_n = 23.45 \times sin\left[360 \times \frac{(284+n)}{365}\right] \tag{8}$$

The last term on the right represents the radiation reflected on the surface from the surrounding, with (ρ) representing the value of the Albedo [21]. **Table 1** lists some typical values of ρ for several types of surfaces [22].

Table 1. Typical Albedo values taken from MOSAiC [22].

Substance or surface	Albedo
Whole earth average	0.3
Fresh snow	0.8–0.9
Sea ice	0.5–0.7
Desert sand	0.4
Green grass	0.25
Bare soil	0.17
Conifer forest	0.08–0.15
Open ocean	0.06
Fresh asphalt	0.04

3. Additional new modelling

Equation (5) describes the performance of mono-facial PV panel facing south or north when installed within the northern and Sothern hemispheres respectively. Two modifications of this equations are needed to make it capable in describing the solar radiation on a bifacial PV facing any arbitrary direction, with the normal to one face making an angle (Ψ) with the East direction. These modifications are:

1) The first and third terms on the right-hand side of Equation (5) are to be multiplied by a factor of (1 + *r*), with *r* being the bifacial ratio, which is defined as the efficiency ratio of the backside of the PV to that of the front side. This modification is to account for the diffusion and Albedo reflected radiations incident on the backside of the bifacial PV. The ratio *r* depends on the types of the PV panel, and it is usually between 0.5 and 0.95.
2) The second term represents the direct radiation when the PV is facing south (*Ψ = 90)* measured from the east direction. This corresponds to receiving maximum radiation at midday. Consequently, and in order to account for installation at any other *Ψ* value, this term is to be multiplied by the factor of *sin(Ψ).* Equation (5) thus becomes:

$$XX(\varphi,\theta,\Psi) = \sum_{n_2}^{n_1}\left\{(1+r)\times D(n,\varphi) + [K_c(n,\varphi) - K_d(n,\varphi)] \times L(n,\varphi) \times [cos(\varphi - \delta_n - \theta)] \times sin\,(\Psi) + \frac{\rho(1+r)}{2} \times (1-\cos(\theta))]\right\} \tag{9}$$

With *XX* being the solar radiation metric for the bifacial PV module.

4. Methodology

Equations (5) and (9) are used to calculate the two percentage gains related to straight bifacial PV fence. Two types of gains are calculated. The first is the annual output energy gain produced by a straight fence furnished with bifacial PV's (O_B) in comparison to the output when the same fence is furnished with monofacial PV's of the same front side efficiency (O_M). Both PV's are considered to be installed vertically and making the same twist angle (ψ) between the normal to the face of the PV panel and the East direction. This is defined as

$$G = 100 \times \left(\frac{O_B}{O_M} - 1\right) \tag{10}$$

The second quantity (S) is the percentage difference between annual output of the bifacial PV's compared to the outputs of an identical mono-facial PV facing south and inclined at the optimum yearly inclination angle ($O_{optimum}$). This quantity is more of an academic rather than a practical value. This is because it compares the performance of PV furnished fences with the maximum possible solar energy output at the same location. This parameter is defined as

$$S = 100 \times \left(\frac{O_B}{O_{optimum}} - 1\right) \tag{11}$$

5. Results

The following presentations are for a straight-line fence making different angles with the reference East-West line. To simplify the presentation of gain data against four independent variables, it may be helpful to categorize these variables into two types. The first category includes physical variables that mainly affect indirect radiation, such as the PV panel bifaciality and the albedo of the surroundings. The second category includes geometric variables that are more related to direct radiation, such as the latitude angle and the PV twist angle with the East-West direction.

The relationship between gain and PV percentage bifaciality for four PV twist angles with the East-West direction, averaged over all albedo values, is presented in **Figure 2**. The figure clearly shows that the gain increases almost linearly with increasing bifaciality for all latitudes and PV twist angles. It also demonstrates the significant impact of bifaciality on gain. Gain values can almost double when the bifaciality is increased from 50% to 95% in most cases.

The effect of latitude on bifacial gain tends to diminish as the PVs become more aligned with the East-West direction. This is evident from **Figure 3a,b**, where latitude appears to have no effect on gain for PVs facing east or west.

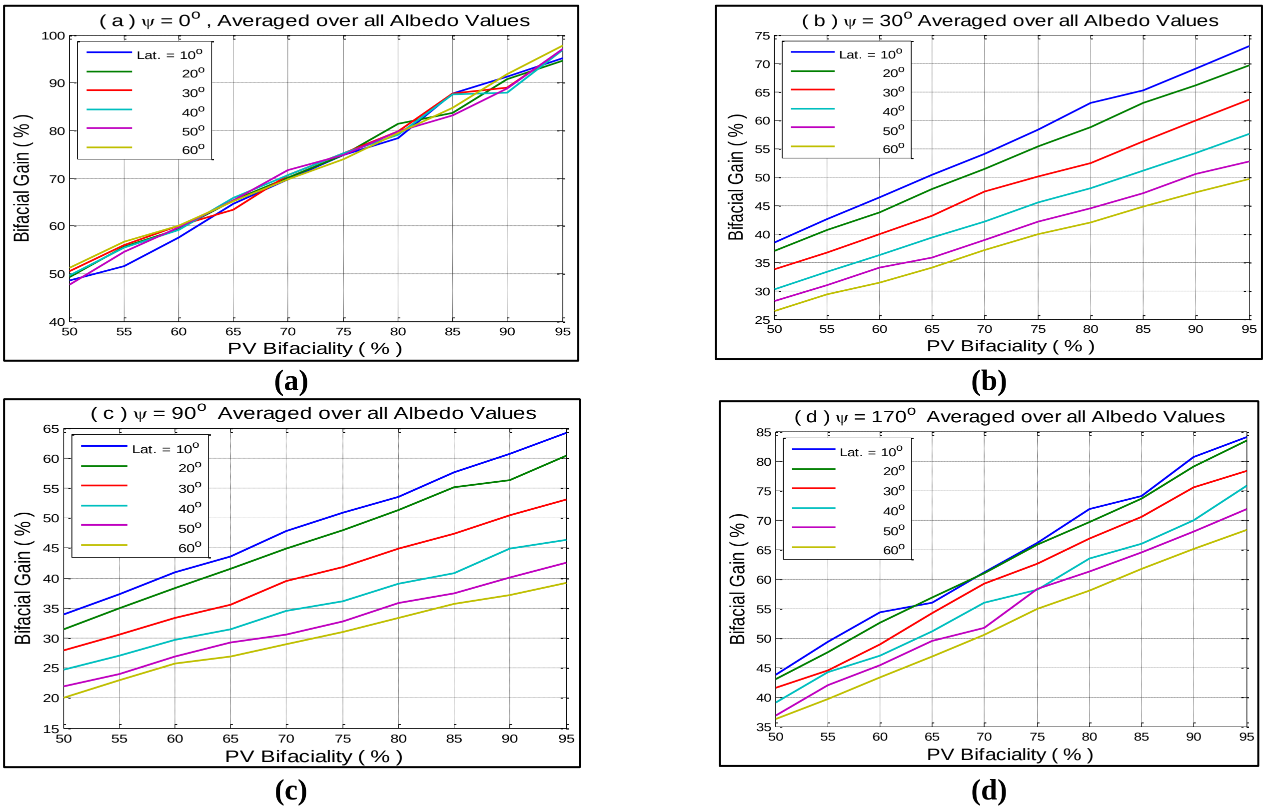

Figure 2. Linear relations of bifacial gain averaged over all albedo values against PV bifaciality for different values of PV twist angles and latitudes.

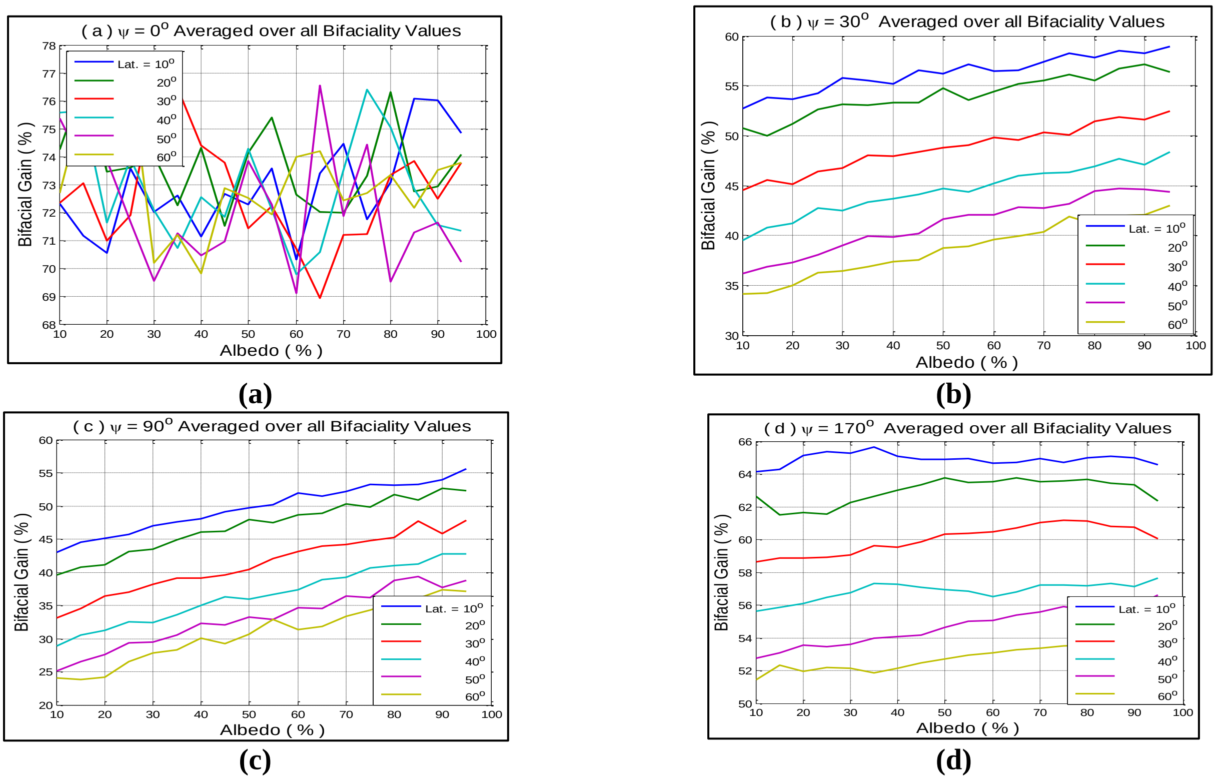

Figure 3. The gain dependence on albedo for four twist angles when the gain is averaged over all bifaciality values.

A similar effect of albedo is demonstrated in **Figure 3**. The bifacial gain, averaged over all bifaciality ratios, shows systematic increases with increasing albedo values for all PV twist angles. However, it is worth noting that the bifacial gains in both **Figures 2** and **3** show significant decreases with increasing latitudes. This is opposite from what one would expect from south-facing PV modules. This point is discussed below.

The above bifacial gain values are relative to corresponding mono-facial PV modules of the same characteristics installed under the same conditions. It is useful to compare bifacial PV outputs to those installed facing south at the optimum inclination angle, as the latter represents the maximum output possible for the particular mono-facial modules under the same conditions. Examples of the two setups are shown in **Figure 4**.

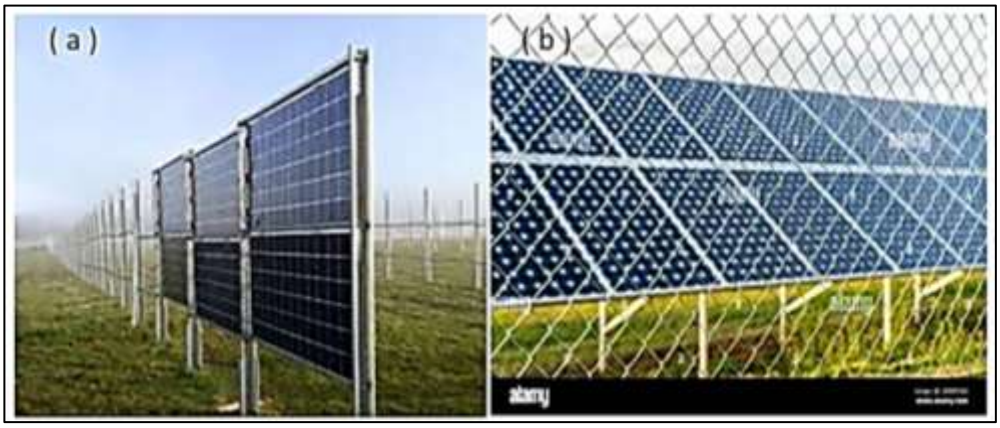

Figure 4. PV fences **(a)** Vertical bifacial facing fence direction; **(b)** mono-facial facing south with optimum inclination angle.

Figures 5 and **6** illustrate the gain of a vertically installed PV module facing four different directions, calculated with reference to a monofacial PV module installed at the optimum inclination and facing south. **Figure 5a–d** and **Figure 6a–d** show negative values of S when the bifacial PV is not oriented southward. This indicates that the output of the bifacial PV is lower compared to the monofacial PV in such cases. This clearly demonstrates that using bifacial PV modules cannot fully compensate for the loss of output caused by deviation from the south-facing orientation. However, as shown in **Figures 5c** and **6c**, *S* becomes positive when the vertically installed bifacial PV is also oriented south. This suggests that the energy loss due to the change from the optimum to a vertical inclination is more than compensated for by the energy collected by the backside of the bifacial PV module.

Interestingly, even when the vertical bifacial PV is facing south, its productivity is less than that of the corresponding mono-facial PV (negative *S* values) at small latitudes. However, the value of S becomes positive at higher latitudes. In these conditions, the bifacial gain relative to the optimum becomes positive because the optimum tilt angle for mono-facial PVs becomes higher and closer to vertical. This results in the front faces of both PVs producing about the same output, while the bifacial PV benefits from additional backside production.

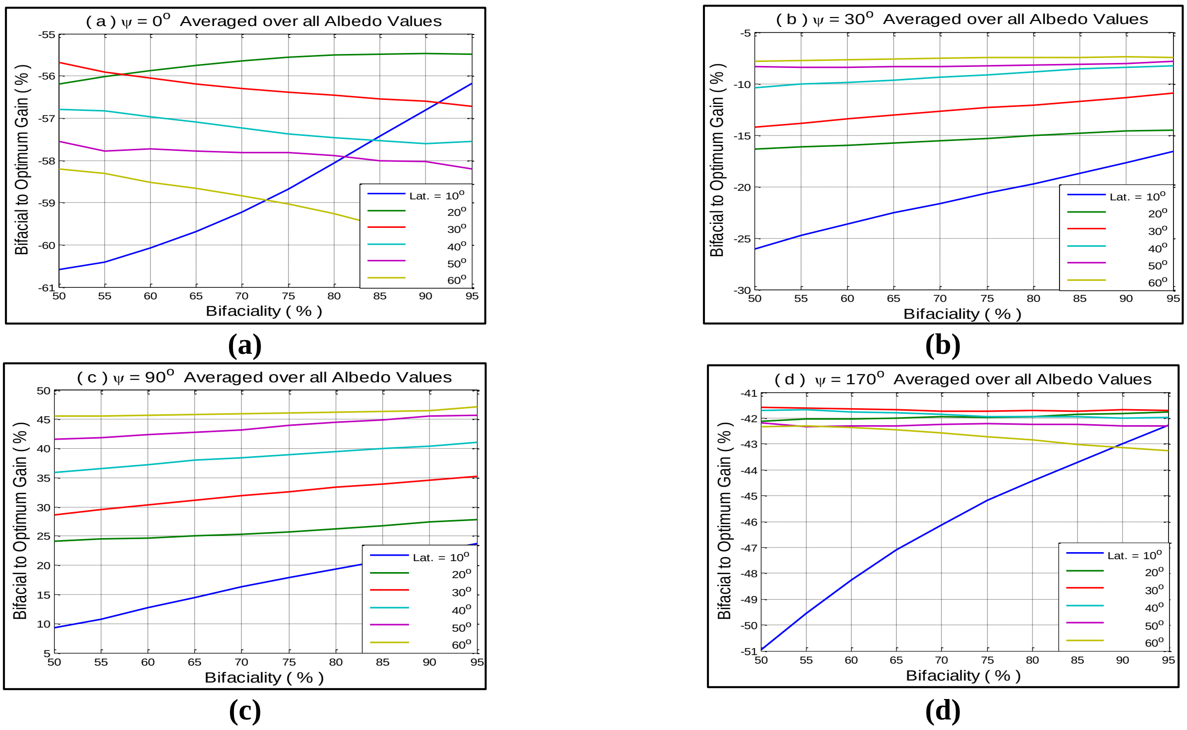

Figure 5. The bifacial to optimum gain dependence on bifaciality for four twist angles when the gain is averaged over all albedo values.

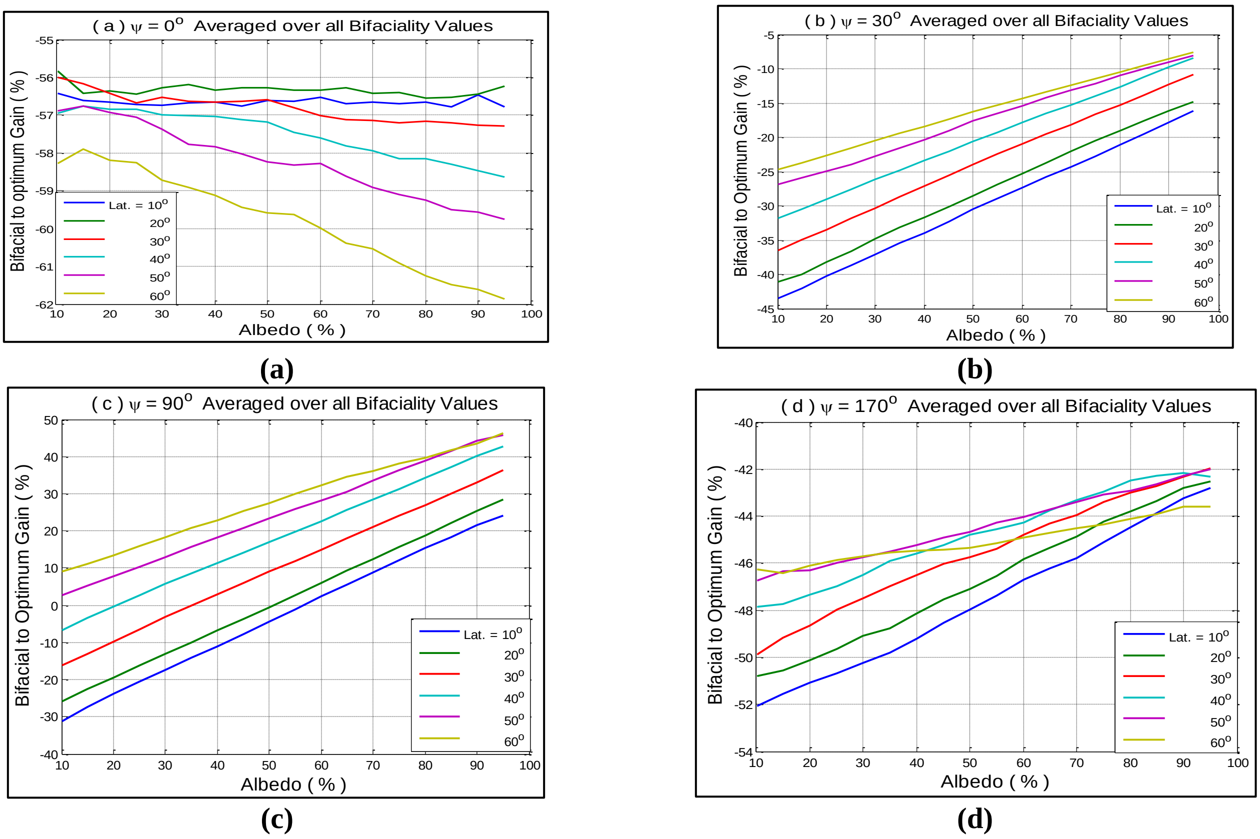

Figure 6. The bifacial to optimum gain dependence on albedo for four twist angles when the gain is averaged over all bifaciality values.

Results in **Figures 2**, **3**, **5** and **6** show that while vertical bifacial PVs can produce significantly higher output compared to their mono-facial counterparts when installed at the same twist angle, their output is still significantly lower than that of mono-facial PVs installed facing south at the optimum inclination.

The physical parameters of bifaciality and albedo are controllable. These can be selected according to available resources. Higher bifaciality PVs can cost slightly more, and the albedo of the surrounding bare soil can be increased by planting grass, for example. However, the geometrical parameters of latitude and fence direction cannot be changed or optimized. Therefore, it is necessary to examine the effect of these two geometrical parameters on bifacial gain in more detail.

The dependence on the bifacial gain on the two geometrical variables is calculated for $(10\ bifaciality) \times (18\ albedo) = 180$ combinations. However, space considerations dictate presenting few only. Consequently, and in order to make our selection of the presentations as objective as possible, we may need to note the following.

1) The advancements in bifacial PV's technology have naturally led to systematic increases in bifaciality ratios in recent years. While some early bifacial modules had bifaciality ratios in the range of 50% to 60%, current market products have bifaciality in the ranges of 75% to 95% [23]. Consequently, the presentation will include typical bifaciality of 55%, 75%, 85% and 95%.
2) The most common surroundings as far as highways, and farm fences are concerned are those associated with asphalt, grass, desert sand, and snow. **Table 1** indicates that these correspond to approximate albedo values of 0.05, 0.25, 0.4, and 0.85 respectively.

Consequently, **Figures 7–10** will show bifacial gain as function of latitude and twist angles for the above sixteen bifaciality—albedo combinations.

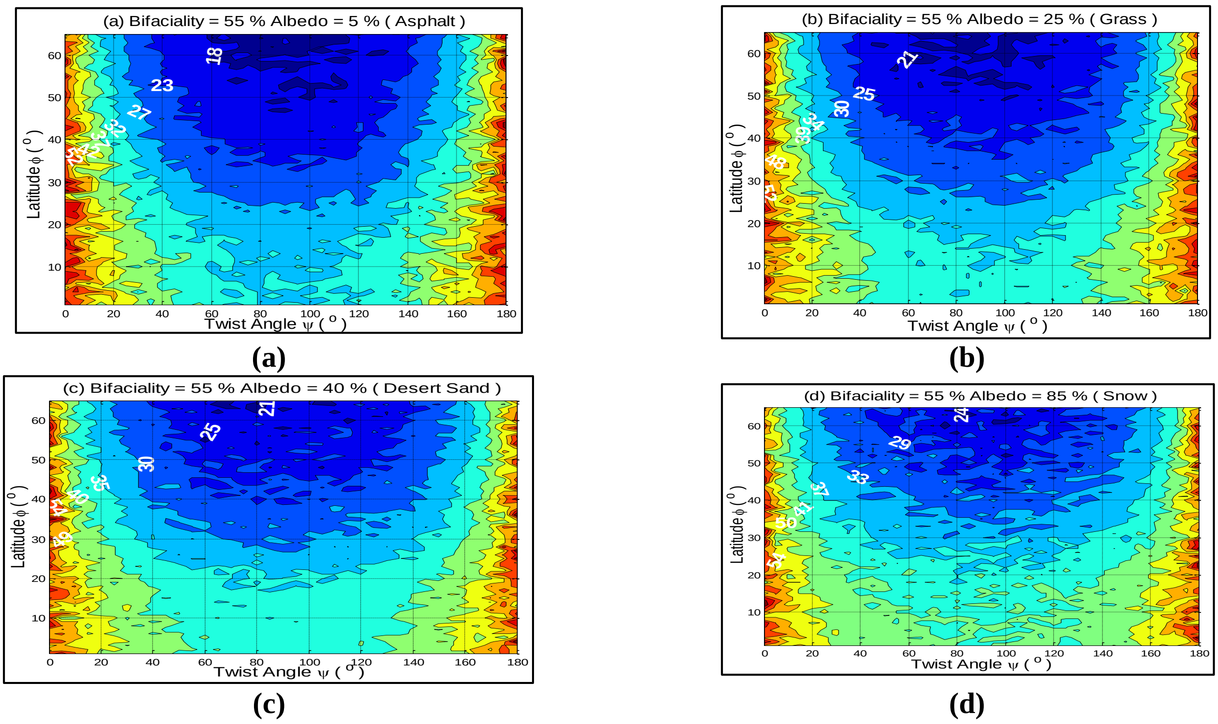

Figure 7. Bifacial gain contours against latitude and twist angles for PV bifaciality of 55% with albedos of **(a)** 5%; **(b)** 25%; **(c)** 40%; and **(d)** 85%.

The general picture suggested by these figures involves the following:

1) Bifacial gains are at highest when the panel is facing East or West.
2) Bifacial gains are higher at large latitudes for all bifaciality, albedo and twist angle values.
3) With all other parameters fixed, the gain increases with increasing bifaciality, and albedo values.
4) In all, bifacial gain values range from about 18% to about 100%. In other words, selecting bifacial over mono-facial for vertical installation is always accompanies by increased productivity to one degree or another.

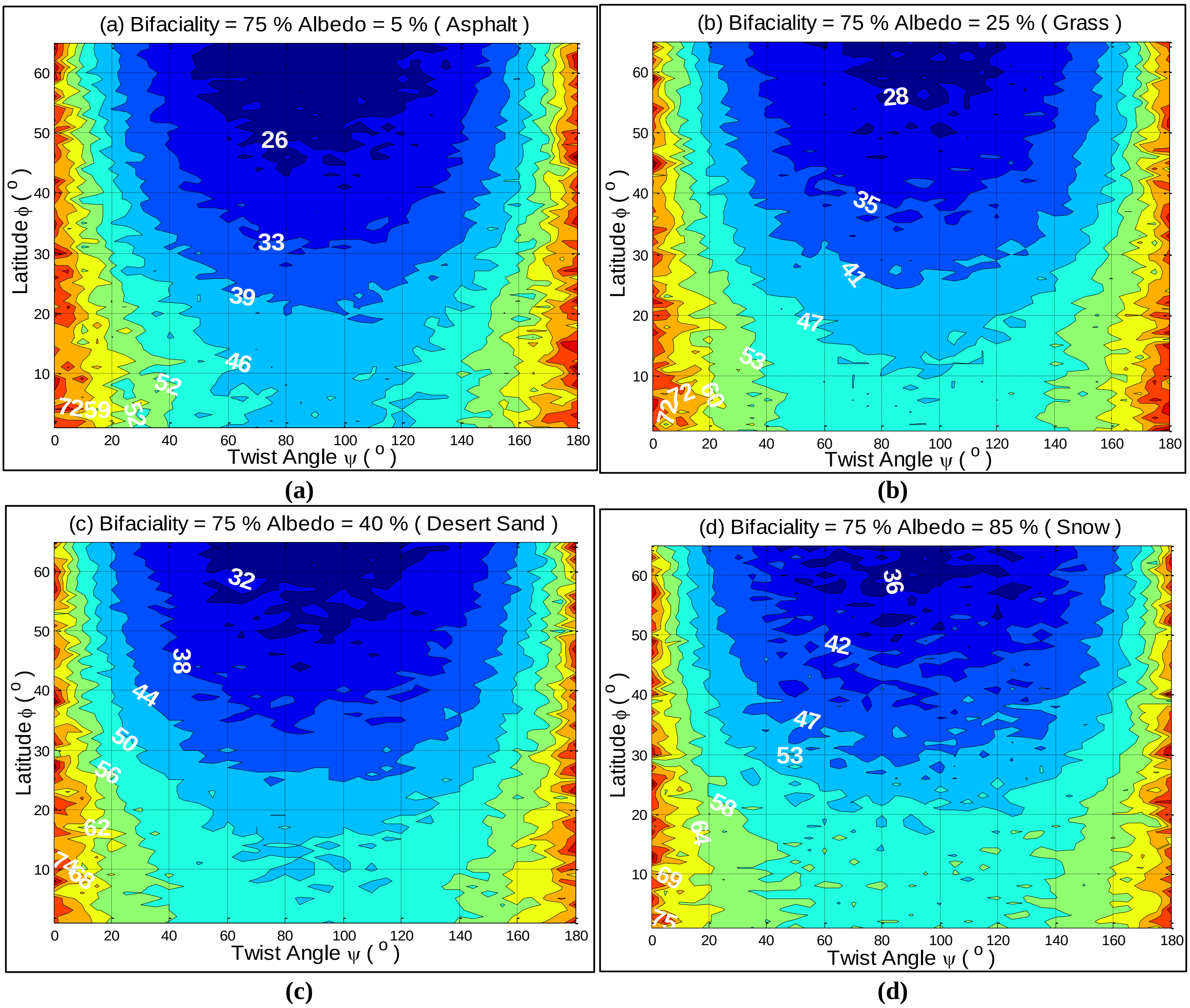

Figure 8. Bifacial gain contours against latitude and twist angles for PV bifaciality of 75% with albedos of **(a)** 5%; **(b)** 25%; **(c)** 40%; and **(d)** 85%.

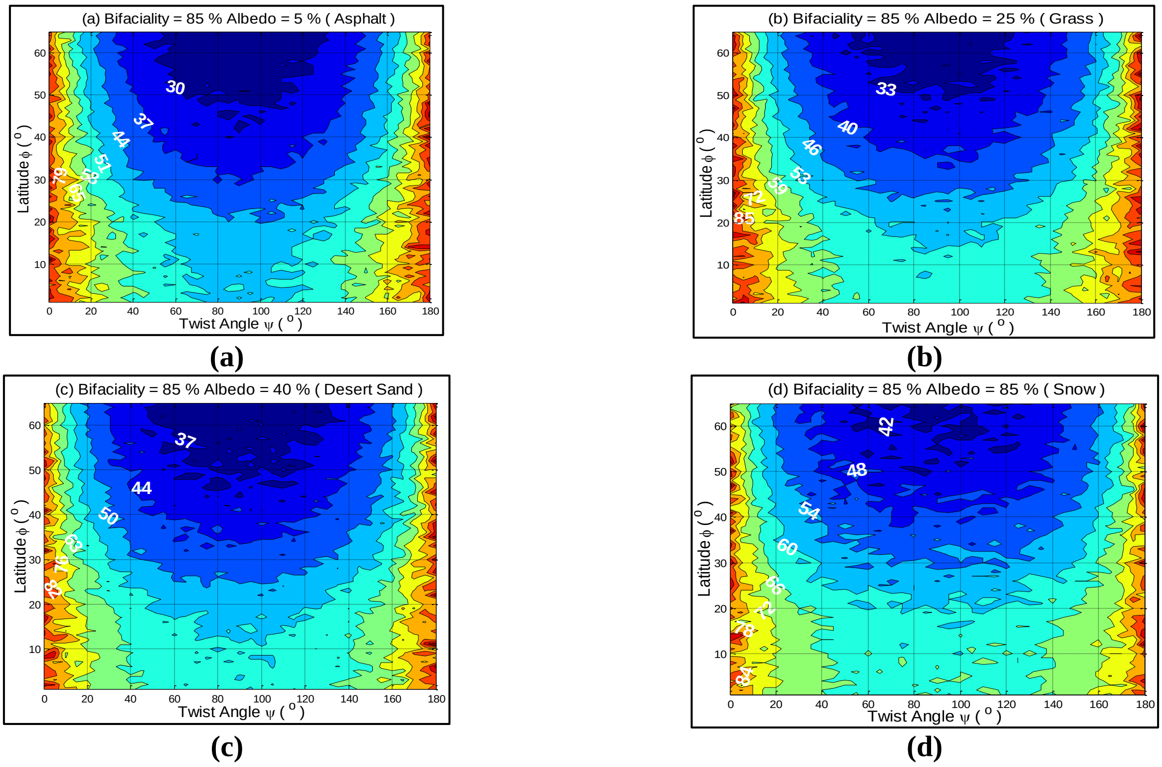

Figure 9. Bifacial gain contours against latitude and twist angles for PV bifaciality of 85% with albedos of **(a)** 5%; **(b)** 25%; **(c)** 40%; and **(d)** 85%.

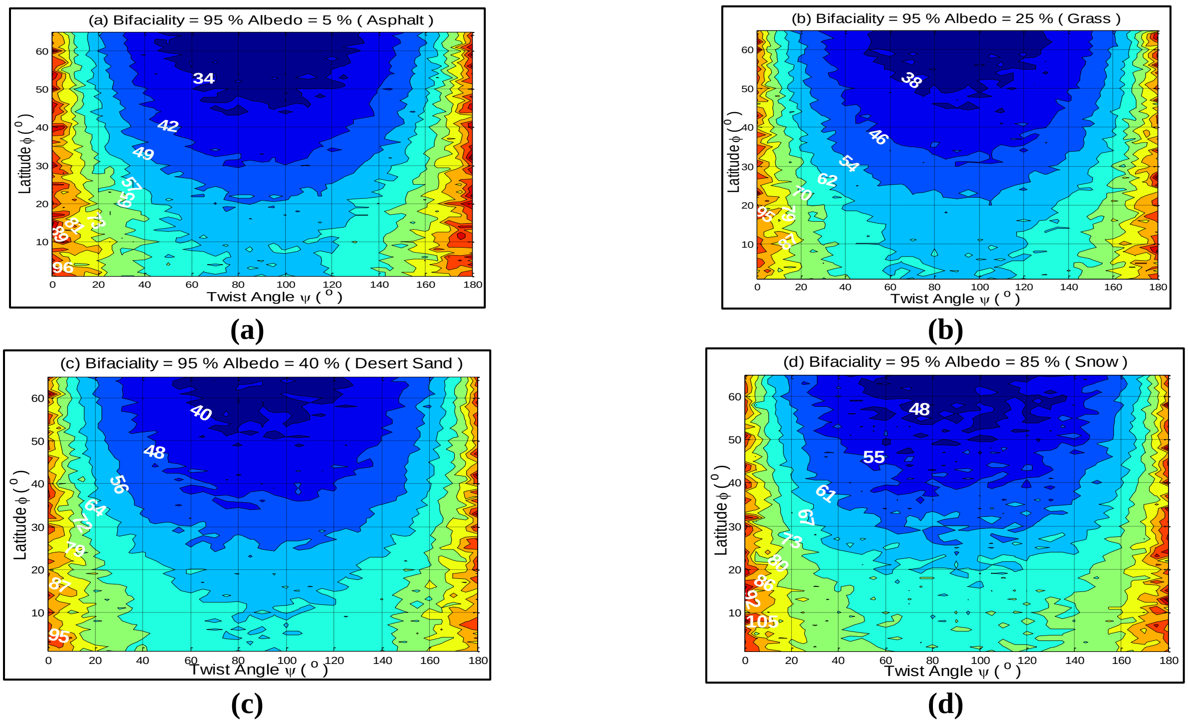

Figure 10. Bifacial gain contours against latitude and twist angles for PV bifaciality of 95% with albedos of **(a)** 5%; **(b)** 25%; **(c)** 40%; and **(d)** 85%.

6. Software and case studies

The above contour plots serve as approximate roadmaps that help in assessing the advantage of selecting bifacial over mono-facial PV modules to furnish straight barriers in any direction. However, a special MATLB software written provides for more precise calculations of gain values for any type of straight or polygonal fence. The software is made freely available on the MATLAB file exchange library together with all its necessary subprograms [24]. The software can be used without much prior knowledge of MATLAB language programming. Once the program is downloaded into the MATLAB active library, it can be activated from the MATLAB work space by entering the following statement, with substituted numerical values of each of the input arguments as described below

[G,S] = Fence _ Efficiency (Latitude, Sides _ Lengths, Sides _ Directions, Albedo, Bifaciality).

Input arguments

The input argument to be provided to the software are

1) Latitude: The latitude angle φ in degrees.
2) Sides_Lengths: A one-dimensional array representing the actual or relative lengths of the sides of the polygonal fence. For a single straight barrier, this will be a single number. For example, a rectangular fence measuring 2 × 3 units should be entered as [2, 3, 2, 3].
3) Sides_Directions: The angles ψ (in degrees) each side makes with the east direction. For instance, if the shorter side of the rectangle mentioned above aligns with the east direction, this argument would be [0, 90, 0, 90]. If this side instead forms a 30° angle with the east, the array would be [30, 120, 30, 120].
4) Albedo: The albedo of the surrounding area, with values ranging from 0.05 to 0.9. Typical values for this parameter are shown in **Table 1**.
5) Bifaciality: The ratio of the backside to the front-side efficiency of the bifacial PV module. This value typically ranges between 0.5 and 0.95, depending on the manufacturer [23].

The program calculates annual energy output gains. However, it can also be configured for monthly gains by modifying the value of $J = 13$ in line 6 of the program. Setting $J = 1$ to $J = 12$ corresponds to each month of the year, while $J = 14$ to $J = 17$ corresponds to the seasons from autumn to summer.

For example, to calculate the bifacial PV gain for rectangular farm fence with sides lengths of 2, 5, 2, and 5 lengths units extending along the east-west, north-south, west-east, and south-north directions respectively, at a latitude of 40º, using PV panels with bifaciality ratio of 0.9 when the surrounding albedo is 0.5, one simply enters the statement

[G, S] = Fence _ Efficiency (40, [2 5 2 5], [0 90 0 90] ,0.5,0.9)

Figure 11 shows four more different shapes and directions of fences, along with the software commands and the two output comparisons of G and S between bifacial PVs with a bifaciality of 0.8 and monofacial PVs. Both types are vertically installed on the fence at the same indicated latitudes with an albedo of 0.3. This procedure can be extended to any polygonal shape with any number of sides. It is noteworthy that G is always positive, indicating that bifacial PVs consistently produce more energy than monofacial PVs when installed identically. G values can exceed 90%.

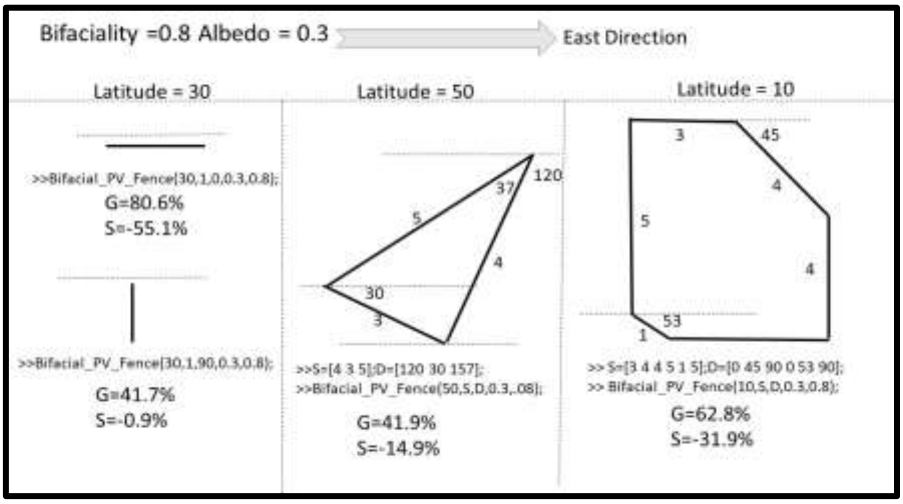

Figure 11. Examples of bifacial gain calculation for different geometrical shapes of fences.

7. Discussion

It is self-evident that model predictions gain much greater credibility when they are consistent with experimental measurement results. Unfortunately, citing experimental measurements of bifacial PV gain at arbitrary twist angles describing situations similar to usual fences installations has proven challenging. However, several studies by various authors have reported experimental measurements of bifacial PV gain with PV panels oriented southward (ψ = 90°) [25–29]. These measurements encompass several latitude angles, and a wide range albedo values, and bifaciality values. It is important to note that most of the experimental gain values discussed here represent averages derived from multiple measurements reported in the cited references, each corresponding to different combinations of latitude, albedo, and bifaciality values. Similarly, the model predictions presented represent mean values, calculated by averaging results from individual simulations based on specific cases. Short descriptions of these measurements and the associated model results are provided below:

Castillo-Aguilella and Hauser [25] measured the average bifacial gain over 30 months in New York and Arizona. The reported average annual bifacial gain is 21.42%. The corresponding model prediction was 18.84%, yielding a difference of 0.2% between the experimental and predicted values.

Du et al. [26] reported results of eight bifacial gain experiments conducted in Shanghai and Tucson, China. Their reported average gain is 18.92%. The corresponding model prediction, using a specified bifaciality factor of 86%, was 20.29%, which is very close to the experimental value.

Hayibo et al. [27] carried out winter bifacial gain measurements in a snowy environment at Delta County Airport (ESC), Escanaba, MI, USA. They reported an average gain of 19.31%. Using an estimated snowy winter albedo of 45% (from **Figure 10a** in the reference) and an approximate bifaciality of 80% in the model resulted in calculated gain of 19.57%, which is in good agreement with the experimental value.

Aksoy and Çalık [28] used the comparison of net energy transferred to the grid between bifacial panels with 90% bifaciality and monofacial setups installed in Konya, Turkey on white ground with an albedo of 0.8. Their results show that the bifacial system produced 15.9% more energy than the monofacial one. Using the same albedo and bifaciality values, the model calculated a gain of 15.97%.

A summary of all above results is presented in **Table 2**.

Table 2. Summary of comparisons between literature bifacial PV gain and model predicted values.

Ref	Location	Latitude (°)	Albedo %	Bifaciality %	Mean experimental gain %	Mean model gain value %
[25]	New York US Arizona US	40.71 34.05	20–95	70–90	18.84	19.06
[26]	Shanghai & Tucson - China	31.23 32.22	9–80	86	20.29	20.55
[27]	Escanaba-US	45.72	45	80	19.31	19.57
[28]	Konya -Turkey	38.0	80	90	15.9	15.97

An additional point that warrants discussion is the economic aspect of adopting bifacial photovoltaic (PV) technology in general and in fences and barriers in particular. As highlighted in the preceding analysis, bifacial PV systems produce 10–30% more energy compared to monofacial PV systems. However, economic considerations play a critical role in determining their suitability for specific applications. Manufacturers such as ROCKSOLAR [29], ItekEnergy [30], and Energy Sage [31] emphasize that the 10%–20% higher upfront cost of bifacial panels is attributed to additional materials and more complex manufacturing processes.

Despite this, the increased efficiency of bifacial panels often offsets their costs, especially in scenarios where installation expenses are comparable. Applications such as PV-equipped fences, noise barriers, and snow barriers exemplify cases where the installation of bifacial panels is unlikely to involve significantly higher costs. In these situations, the enhanced energy output of bifacial systems makes them an economically viable option. However, this may not always hold true for rooftop PV installations, where the direct mounting of monofacial panels typically results in lower installation costs in most cases.

8. Conclusions

- This study provides a practical framework for unlocking the potential of bifacial photovoltaic (PV) systems in innovative applications, such as farm fences, highway barriers, noise barriers, and snow barriers. By demonstrating bifacial energy gains ranging from 10% to 80%, particularly in high-latitude regions.
- A key outcome of this work is the development of specialized software capable of accurately estimating bifacial gain, accounting for critical factors such as latitude, albedo, bifaciality, and structural geometries. This tool equips stakeholders with actionable insights, addressing a core challenge in large-scale PV energy deployment: the extensive land area traditionally required for installations.

- By repurposing existing structures such as fences and barriers, this approach eliminates the need for additional land, offering a groundbreaking solution for space-efficient renewable energy generation. The economic advantages are equally compelling: the enhanced energy yield of bifacial systems, coupled with the removal of land acquisition costs, positions these installations as a cost-effective and sustainable choice for the future of PV technology.
- This work not only advances the understanding of bifacial PV performance but also charts a path toward smarter, more integrated energy solutions that align with global sustainability goals.

Author contributions: Conceptualization, AAA and ZTA; methodology, AAA and ZTA; software, XX; validation, AAA and ZTA; formal analysis, AAA and ZTA; investigation, AAA and ZTA; resources, AAA and ZTA; data curation, AAA and ZTA; writing—original draft preparation, AAA; writing—review and editing, ZTA; visualization, AAA; supervision, AAA and ZTA; project administration, AAA. All authors have read and agreed to the published version of the manuscript.

Conflict of interest: The authors declare no conflict of interest.

References

1. Becquerel M. Mémoire sur les effets électriques produits sous l'influence des rayons solaires. Comptes rendus hebdomadaires des séances de l'Académie des sciences. 1839; 9: 561-567.
2. Starowicz A, Rusanowska P, Zieliński M. Photovoltaic cell—the history of invention—review. Polityka Energetyczna—Energy Policy Journal. 2023; 26(1): 169–180. doi: 10.33223/epj/161290
3. IEA. In 2023, solar PV alone accounted for three-quarters of renewable capacity additions worldwide. Available online: https://www.iea.org/energysystem/renewables/solar-pv (accessed on 10 June 2024).
4. IEA. Executive Summary. Available online: https://iea-pvps.org/snapshot-reports/snapshot-2023/ (accessed on 12 June 2024).
5. IEA. Renewable Energy Market Update Outlook for 2023 and 2024. Available online: https://www.iea.org/reports/renewable-energy-market-update-june-2023/executive-summary (accessed on 13 June 2024).
6. Hezel R. Novel applications of bifacial solar cells. Progress in Photovoltaics: Research and Applications. 2003; 11(8): 549–556. doi: 10.1002/pip.510
7. Libal J, Kopecek R. Bifacial Photovoltaics: Technology, Applications and Economics. Institution of Engineering and Technology; 2018. doi: 10.1049/pbpo107e
8. Matarneh G A, Al-Rawajfeh M A, Gomaa M R. Comparison review between monofacial and bifacial solar modules. Technology audit and production reserves. 2022; 6(1(68)): 24–29. doi: 10.15587/2706-5448.2022.268955
9. Braga D S, Kazmerski L L, Cassini D A, et al. Performance of bifacial PV modules under different operating conditions in the State of Minas Gerais, Brazil. Renewable Energy and Environmental Sustainability. 2023; 8: 23. doi: 10.1051/rees/2023021
10. Chunduri S K, Schmela M. Bifacial Solar Module Technology 2018 Edition. Available online: https://www.researchgate.net/publication/354813723_Bifacial_Solar_Module_Technology_2018_Edition_-_Getting_Ready_For_Much_Higher_Yields_With_Bifacial_Modules?channel=doi&linkId=614dd2fdf8c9c51a8aeec8ab&showFulltext=true (accessed on 13 June 2024).
11. Lorenzo E. On the historical origins of bifacial PV modelling. Solar Energy. 2021; 218: 587–595. doi: 10.1016/j.solener.2021.03.006
12. Eguren J, Martínez-Moreno F, Merodio P, et al. First bifacial PV modules early 1983. Solar Energy. 2022; 243: 327–335. doi: 10.1016/j.solener.2022.08.002
13. RenewSys. Bifacial Solar Cells. Available online: https://www.renewsysworld.com/post/bifacial-solar-cells (accessed on 11 July 2024).

14. Alternergy. Bifacial solar panels: What are they and are they worth it? Available online: https://www.alternergy.co.uk/blog/post/bifacial-solar-panels-what-are-they (accessed on 2 July 2024).
15. Issaq S Z, Talal S K, Azooz A A. Empirical modeling of optimum tilt angle for flat solar collectors and PV panels. Environmental Science and Pollution Research. 2023; 30(33): 81250–81266. doi: 10.1007/s11356-023-28142-3
16. Langels H, Gannedahl F. BiFacial PV Systems: A technological and financial comparison between BiFacial and standard PV panels. Available online: https://www.semanticscholar.org/paper/BiFacial-PV-Systems-%3A-A-technological-and-financial-Langels-Gannedahl/05e95ec78d3f5676c4307713c3088d84af0db6bb (accessed on 13 June 2024).
17. Kumbaroğlu G S, Çamlibel M E, Avcı C. Techno-economic comparison of bifacial vs monofacial solar panels. Engineering Structures and Technologies. 2021; 13(1): 7–18.
18. HOMER. Published Solar Data.HOMER Energy. Available online: https://homerenergy.com/products/pro/docs/3.15/index.html (accessed on 12 July 2024).
19. Orgill J, Hollands K. Correlation equation for hourly diffuse radiation on a horizontal surface. Solar energy. 1977; 19(4): 357–359.
20. Duffie JA, Beckman W A. Solar engineering of thermal processes. Wiley New York; 1980.
21. Widén J, Munkhammar J. Solar Radiation Theory. Uppsala University; 2019.
22. MOSAiC. Quick Bite: Albedo Comparison. University of Colorado Boulder. Available online: https://mosaic.colorado.edu/quick-bite-albedo-comparison (accessed on 3 August 2024).
23. Guerrero-Lemus R, Vega R, Kim T, et al. Bifacial solar photovoltaics—A technology review. Renewable and Sustainable Energy Reviews. 2016; 60: 1533–1549. doi: 10.1016/j.rser.2016.03.041
24. Azooz AA. Software for calculating energy gain when using bifacial PV" MATLAB file exchange library. Available online: https://www.mathworks.com/matlabcentral/fileexchange/171169-software-for-calculating-energy-gain-when-using-bifacial-pv (accessed on 13 June 2024).
25. Castillo-Aguilella J E, Hauser P S. Multi-Variable Bifacial Photovoltaic Module Test Results and Best-Fit Annual Bifacial Energy Yield Model. IEEE Access. 2016; 4: 498–506. doi: 10.1109/access.2016.2518399
26. Du H, Hao G, Li H, et al. Analysis of annual bifacial gain in energy and annual energy yield of bifacial modules at low latitudes. International Journal of Green Energy. 2021; 18(15): 1632–1644. doi: 10.1080/15435075.2021.1930000
27. Hayibo K S, Petsiuk A, Mayville P, et al. Monofacial vs bifacial solar photovoltaic systems in snowy environments. Renewable Energy. 2022; 193: 657–668. doi: 10.1016/j.renene.2022.05.050
28. Aksoy M H, Çalik M K. Çift Yüzlü Fotovoltaik Panellerin Farklı Zemin Koşullarında Performansının İncelenmesi. Konya Journal of Engineering Sciences. 2022; 10(3): 704–718. doi: 10.36306/konjes.1116729
29. Bifacial vs. Monofacial Solar Panels: Which One is Right for Your Solar System? Available online: https://rocksolar.ca/blogs/news/bifacial-vs-monofacial-solar-panels-which-one-is-right-for-your-solar-system (accessed on 13 June 2024).
30. Heltsley K. Bifacial Solar Panels vs Monocrystalline Solar Panels. Available online: https://www.itekenergy.com/solar-panels/bifacial-solar-panels-vs-monocrystalline-solar-panels/ (accessed on 13 June 2024).
31. Tan D. Monofacial vs. Bifacial Solar Panels: Which is Best for Your Solar Setup? Available online: https://directsolarpower.com/blogs/learning-center/monofacial-vs-bifacial-solar-panels-which-is-best-for-your-solar-setup (accessed on 13 June 2024).