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Modeling The Energy Yield of Bifacial Photovoltaic Systems Considering Ground Albedo

A. Abduraimov,
A. Kuchkarov
Fergana State Technical University, Fergana, Uzbekistan
avazavazbek18@gmail.com

Abstract
The article aims to present an analysis of the influence that geometric and optical parameters exert on the energy efficiency of bifacial PV modules. The installation height, tilt angle, and surface albedo have been studied with experimental data and with a proposed mathematical model. The results confirm that increasing the installation height to a range between 0.7 m and 1.0 m and choosing an optimal tilt angle between 30° and 35° reduces power losses due to uneven illumination by over 25% and improves energy production. The spectral characteristics of the surface albedo have a profound effect on the value of the bifacial enhancement. The satisfied results of the calculated and experimental tests (R^2>0.9) confirm the applicability and viability of the proposed model.

Keywords: Bifacial solar panels; surface albedo; installation height; tilt angle; mismatch losses; energy generation modeling; spectral reflectance.

Introduction

Bifacial Photovoltaic Modules: These modules can collect power not only from their face but also from their back. This improves the output from each surface by up to 5-30% under natural conditions and up to 30% under optimal conditions. Moreover, they also make optimal use of diffuse light and reflected light from surrounding surfaces. Experiments have confirmed that under cloudy conditions with low-intensity illumination, the relative output ratio for bifacial modules is higher compared to single-facing modules [1]. These features have sparked an explosion of interest in Bifacial Photovoltaic Systems over the past ten years. Today, with advances in technology and reductions in module prices, Bifacial systems are becoming the new norm from being an innovation. According to predictions made by the International Roadmap for Photovoltaics (ITRPV), bifacial solar cell market share may touch an astonishing figure of 85% by 2032. Moreover, bifacial panels are actively being employed on a larger scale worldwide, and the bifacial modules market size is predicted to reach $187 billion by 2028 from $92 billion in 2023. [2]. Currently, bifacial photovoltaic modules are equally efficient at providing power not only from the front side of the solar panels but also from the reverse side of the panels, resulting in increased efficiency compared to traditional monolithic panels [2]. It has also been observed that the performance of bifacial solar panels is influenced by the albedo of the surface on which the solar panels are positioned, i.e., the reflectivity of the surface. It has been observed that the reflected solar radiation on the reverse side of the solar panels will be increased by the high value of albedo, resulting in increased efficiency. Therefore, while calculating the overall efficiency of the solar panels, the reflectivity of the coating layer needs to be taken into consideration because the value of albedo of grass or soil is typically in the range of 0.2-0.3, whereas the value of albedo of the white surface can be as high as 0.8 [3, 4]. A number of studies stress the importance of a correct albedo modeling. For example, Su et al. remark that dynamic variations of albedo during the day complicate the assessment of production, and the use of average values can lead to an overestimation of energy by up to 19.4% [5,6]. Ortiga et al. stress the fact that short-term albedo measurements may show fluctuations of up to 60% within a single day [7]. Inadequate assessment of albedo leads to big errors in return assessment: e.g., the model of Koskung & Demir demonstrated increase of annual output of floating double-side installation by 12.4% compared with a monolithic one due to reflected radiation [8]. D'Alessandro et al. (2024) proposed improved albedo reflectance models that allow for a more accurate assessment of the contribution of backirradiation to the general generation of bifacial modules [9]. The authors have shown that simplified assumptions of reflectance homogeneity may result in large mistakes in energy production forecasting. The same conclusions were arrived at by Su et al. (2024), who experimentally showed that diurnal albedo variations greatly impact the energy yield of the bifacial systems and should be considered in modeling [10]. A considerable contribution to developing the methods of bifacial gain calculation was made by Pelaez et al. (2019), who presented the development and verification of a ray tracing-based model [11]. This method enabled consideration of installation geometry, self-shading, and backside irradiation unevenness in detail. The same influence of installation parameters on the efficiency of bifacial photovoltaic systems has been demonstrated by and Bhang and Lee (2018), depending on such variables as mounting height, tilt angle, and module placement configuration [12, 13]. For example, analysis of twenty analogous studies shows that the increase in the level of generation of a bifacial system, under appropriate conditions, can reach a percentage between 5 and 30% [14]. Modeling of a bifacial photovoltaic system can be carried out using special software, namely, PVsyst, SAM, Radiance, etc., which considers the geometric parameters of the installation and the geographical parameters of the site, namely, azimuth, angle of tilt, height of installation above the ground level, and coefficient of albedo. For instance, the report of the NREL declares the following: Energy gain depends on site configuration and surface albedo, and the software named PVsyst can be used for the calculation of the energy output of photovoltaic systems [15].

Accordingly, taking into account the climatic characteristics of the Fergana Valley (the average annual insolation reaches ~1500–1550 kW·h/m²) [16], considering the necessity to enhance the energy production of solar power plants in this region, the problem to be solved is the modeling of energy production with regard to the actual albedo coefficients of the soil. This makes the optimal tilt and orientation of the panels possible in the Fergana Valley using the PVsyst software.

2. MATERIALS AND METHODS

The PVsyst software tool, specifically version 8.0, which helps perform detailed calculations on bifacial systems, was used for modeling. The software takes into account the distribution of diffuse radiation present in the sky, together with an estimate of the isotropic re-emitted radiation present on the surface (Lambert model). The "view factor" or the fraction of reflected radiation that reaches the other side, is calculated at each point on the ground. During calculation, the total flux is obtained by adding the flux obtained from the other side in addition to the insolation on the front surfaces, depending on the bifacial coefficient of the modules [17].

Simulation location: Fergana Valley, Uzbekistan. Values for the average annual solar radiation resource (~1500–1550 kWh/m² per plane) for climate data were used. Data on PVGIS/Climate-SAF for the latitude and longitude of Fergana were used [18].

Module and installation PV module: The Longi Solar LR5-72HGD-585M, a bifacial, glass-on-glass, TOPCon module, is chosen for the present application. Nominal power is 585 W (95% ± 0% kW·h, efficiency ~ 22.6% by module area). The angle of temperature coefficient Pmax is -0.28% /°C. The module is of high voltage (1,500 V, 144 cells) and of reinforced structure designed for snow load 5,400 Pa. According to the description provided by the manufacturer, "additional output from reflected surfaces, increasing overall output" should be attributed to the double-sided design of the panels [19].

System configuration: The panels are ground-mounted and fixed. The module azimuth is set to +13° (oriented east of south). Simulations were conducted for tilt angles of 30°, 35°, 40°, and 45°. A 5° step was used to evaluate the effect of tilt on annual energy. The spacing between rows was chosen to minimize mutual shading at the selected GCR. In PVsyst, a fixed albedo of 0.20–0.25 was set for the ground, corresponding to light soil/grass.

Meteorological data: The calculations were made using data from the PVGIS/Climate SAF global database on global irradiance, diffuse irradiance, temperature, and other parameters. The region of the valley has a continental climate with low precipitation levels, leading to an active plant growth season with an albedo of ~0.2. The calculations also consider the sensitivity of the obtained yield to changes in the albedo (~0.3 and 0.4, corresponding to the albedo of light-colored sand or concrete).

Calculation Methodology: The energy output generated for each respective configuration has been calculated by employing algorithms incorporated by PVsyst. The amount of total electrical energy generated by the system annually (in kWh) has been calculated by the program for respective tilt angles, with losses being calculated due to mutual shading and module operating temperatures. The calculations by PVsyst assumed uniform surface radiation and took into consideration shadow losses on rows with the infinite sheds model. The results were compared with each other and with a typical monolithic (albedo = 0) option and were used to compare the gain with two-sidedness.

Accordingly, the relevant model enables us to study the effect of the tilt angles and albedo of the soils on the annual energy output of the bifacial PV system in the Fergana Valley and determine how to attain the optimal conditions for maximizing the energy output.

3. RESULTS

Based on this model, it was calculated that in the entire range from 30 to 45 degrees, annual loss due to improper panel inclination from the optimal angle would be insignificant (a few percent).

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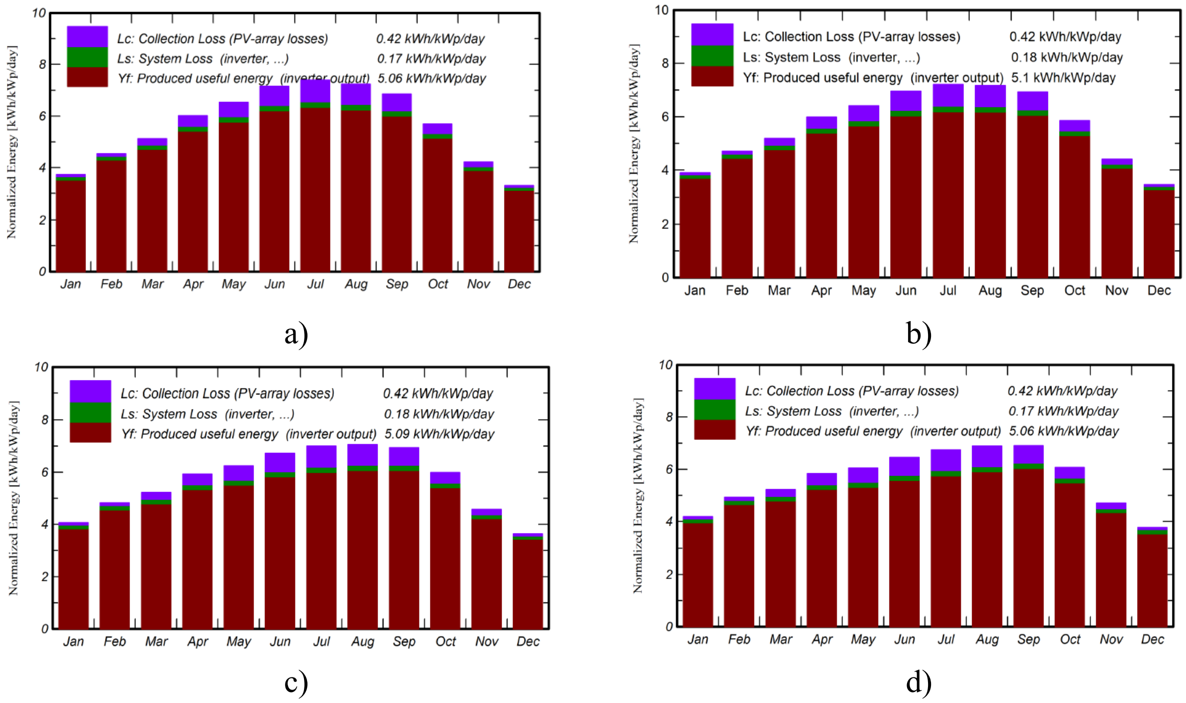
In addition, it was discovered that the optimal generation was observed when the panels' inclination was 35 degrees, which corresponded to 1860 kW·h/kW$_p$ per year. Even when this angle was shifted to 40 degrees, similar results were achieved, 1859 kW·h/kW$_p$ per year. As compared to this, at 30 degrees, slightly lower results are reported, 1848 kW·h/kW$_p$, and at 45 degrees, results are even lower, 1845 kW·h/kW$_p$. It means that the deviation of these angles from the optimal angle is not significant, i.e., even if the panels are installed under an angle, it would not affect generation results due to the relatively large optimal angle plateau, i.e., even 30-40 degrees would yield almost optimal results.

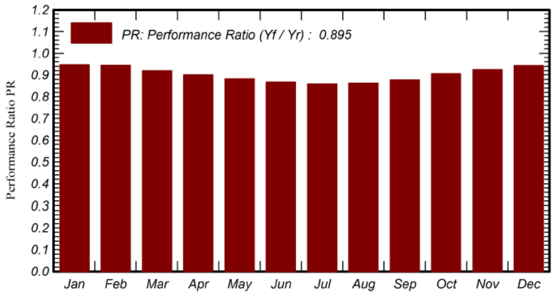
Based on the results of the PVsyst simulation, it is possible to establish the annual output and efficiency of such a bifacial PV system with different module installation angles. It is obvious that varying from the optimal angle by ±10° results in relatively insignificant changes. Optimization of the annual output is attainable at a 35° angle. That is close to the geographic latitude of this region. In this case, it is possible to obtain up to 3,265 kW·h. However, any deviations from this norm by 30° (by reducing the angle) or 45° (by elevating it) lead to a loss of 20-30 kW·h. It is obvious that this is less than 1% of the optimal. Therefore, within the provided range of orientations, it is obvious that there is not significant variation in the total annual output of the bifacial PV system. Based on this information, it is obvious that the choice of the tilt angle from 30° to 45° does not have significant effects. Analysis of the results demonstrates significant efficiency.



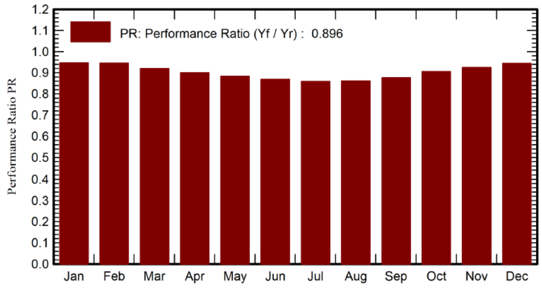
a) b) c) d)

Fig. 1. Normalized output per installed capacity at different tilt angles: a) 30º; b) 35º; c) 40º; d) 45º.

The estimated value of specific yield is around 1,850 kW·h for each 1 kW$_p$ installed power unit annually. This means that there is an excellent utilization potential from solar power at a chosen location. Performing factors (PR), which range between 89.5–89.6%, are calculated for each of the considered tilt angles (see Table 1). The value of a performing factor higher than 0.89 implies that total power losses, including those corresponding to module heating, inverter inefficiency, etc., do not exceed ~10-11% of theoretical power generation volume. At the same time, an interesting situation is that, with bifacial modules, their role is not so much that of increasing the performing factor value as simply that of increasing its absolute value, because, as seen above, its calculation includes all insolation on the front side, while additional insolation on the back side is beyond its definition.



a)



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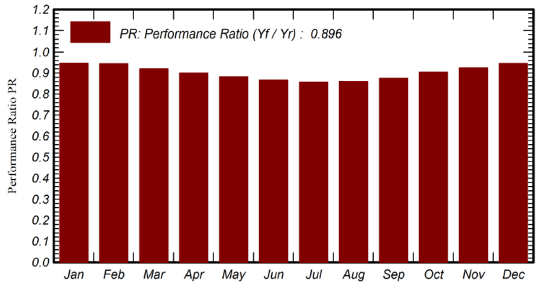

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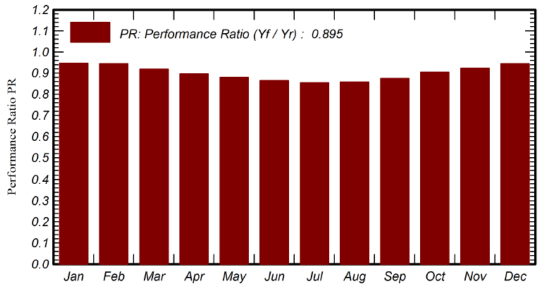

d)

Fig. 2. Performance coefficient PR at different inclination angles: a) 30º; b) 35º; c) 40º; d) 45º.

The bifacial generation increase can be estimated in comparison to a hypothetical system of the same modules but no bifacial effect. For an albedo of 0.2, the additional energy from the rear of the modules gave an increase of about 8-10%. Hence, the bifacial photovoltaic system generated roughly one-tenth more electricity than the single-facing similar system.

Hence, from the point of view of making use of maximum energy, the ideal angle for the installation of the bifacial solar modules would be in the range of 35-40°. In fact, within the acceptable level of accuracy of the PVsyst calculation tool, the recommended angle for the installation of the bifacial solar module would be about 35°, considering that the measure would ensure maximum annual electrical production. In fact, the recommended angle of about 35° for the installation of the solar panel would reduce the chances of severe overheating of the solar panel, considering that the suggested angle would ensure the maximum utilization of the solar radiation reflected from the ground surface, reaching the back of the panel. A solar panel installed at an angle of about 35° would be useful for the removal of dust from the panel.

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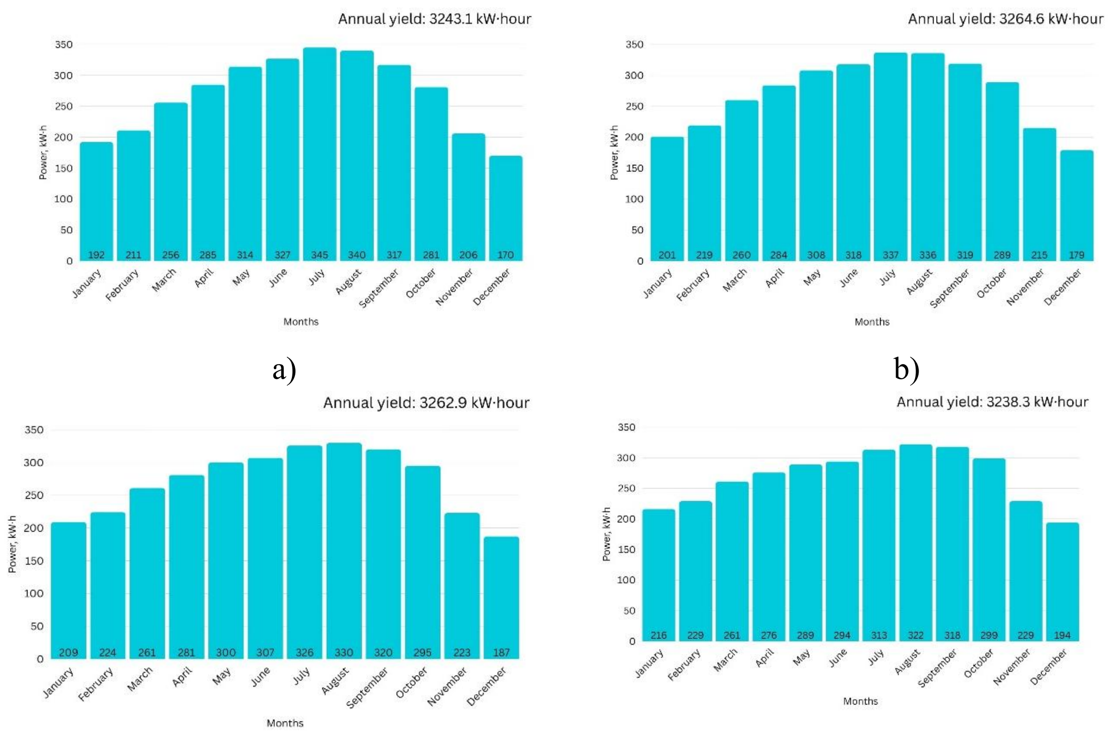
Table-1 PVsyst modeling results: annual output and performance coefficient (PR) for different panel installation angles (bifacial module, Fergana).

Tilt angle, °	Module type	Specific annual output, kWh/kW$_p$	PR, %
30	Bifacial	1848	89,5
35	Bifacial	1860	89,6
40	Bifacial	1859	89,6
45	Bifacial	1845	89,5

As this table shows, an angle of 35° ensures the highest specific generation level (~1860 kW·h/kW$_p$ per year), reaching a maximum PR of ~89.6%. An angle of 40° generates essentially the same result (< 0.1% percentage difference). For 30° and 45° angles, this generation level will be slightly lower (by ~ 0.7-1% from the maximum).

Hence, from an energy point of view, the optimal installation angle for the bifacial modules in the Fergana region should be in the range of 35 to 40 degrees. However, considering the accuracy of the PVsyst modeling tool, the installation angle of around 35 degrees should be recommended to ensure the optimal energy generation from the PV array. This is more in line with the geographical position of the region and at the same time is inclined sufficiently to allow more of the unreflected sun rays from the ground to hit the rear side of the panel. In addition to this, the PV array can be placed at an installation angle of around 35 degrees to allow the removal of the dust from the panels during the rain and reduce the chances of severe overheating of the modules.



a) b) c) d)

Fig. 3. Monthly distribution of electricity generation of the photovoltaic system at different tilt angles of the solar panel: a) 30º; b) 35º; c) 40º; d) 45º.

From the analysis of the results, the tilt angle has a significant impact on the annual electrical power produced and the overall change in the season. In the winter season, the values are minimum, while in the summer season, from June to August, the values are maximum due to the total radiation and long days.

At an angle of 30° (a), the generated power is 3,243.1 kW·h annually. The maximum generated power is realized in July. The change in tilt angle from 30° to 35° (b) results in an increase in generated power to 3,264.6 kW·h, showing that solar energy is better harvested in transitional seasons. A similar value of generated power is realized at a tilt angle of 40° (c), which is 3,262.9 kW·h, with a uniform power generation curve experienced during spring and summer.

If the tilt angle of the panel increases further to 45°, the annual energy production falls to 3238.3 kW·h, owing to the decrease in the panel's receipt of solar radiation during the summer, even though there is a slight improvement in the winter.

In general, based on the results obtained, it should be noted that the optimal range for the angles of solar panels, taking into consideration a set of conditions, is 35–40°, which ensures maximum energy production. The difference between the options is up to 1–1.5%, and while designing the photovoltaic system, any deviations are critical with regard to energy efficiency.

4. CONCLUSION

It follows from the described study that the efficiency of the photovoltaic bifacial modules is mainly determined by the geometry of installation and optical properties of the surface underneath. Insufficient mounting height and a non-optimal tilt angle lead to an enhanced backside irradiation unevenness and, hence, enhanced power losses due to misorientation. Experiments and calculations conducted within this work showed that the placement of modules at approximately 0.7–1.0 m high and at a tilt angle of 30–35° ensures an optimum balance between additional generation and losses.

It is evident that surface albedo has a major impact on the magnitude of bifacial gain, not only due to its integral value but also because of spectral composition. In this regard, surfaces with high shortwave reflectivity provided an increase in total energy production of up to 15–20%, while low-albedo coatings showed a minimal effect. The high accordance of modeling results and experimental data testifies to the adequacy of the developed model and its suitability for practical calculations. Generally speaking, the obtained results create a reliable scientific and practical basis for forecasting, optimization, and feasibility studies regarding the use of bifacial photovoltaic systems in real-life operating conditions.

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