The effects of surface albedo and photovoltaic system tilt angle on improving light energy utilization efficiency

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Article Info

Article history:

Received Sep 1, 2025
Revised Jan 27, 2026
Accepted Feb 15, 2026

Keywords:

Albedo
Ground reflector
Optimum tilt angle
PVsyst
PV system
Yearly tilt angle

ABSTRACT

The ground-surface reflection (albedo) significantly influences the amount of solar radiation absorbed by photovoltaic panels and, thus, the optimum tilt angle for maximizing annual energy generation. Nevertheless, the majority of design models presume a constant albedo value, therefore could not accurately represent actual field conditions. This study aims to identify the optimal tilt angle for each albedo value that maximizes the annual energy output of a stationary on-grid photovoltaic system of 20.48 kWp installed in Baghdad, Iraq. Seven albedo values, varying from 0.09 to 0.87, were simulated using PVsyst software, with the reference case established at an albedo of 0.2 and a tilt angle of 31°. The results indicate that the optimum tilt angle is directly proportional to the surface reflection. For albedo levels below the reference of 0.2 (0.18 and 0.09), increased energy generation occurred at reduced tilt angles of 30.5° and 29°, respectively. Conversely, for increased albedo values (i.e., exceeding the reference of 0.2, spanning from 0.25 to 0.87), greater tilt angles were necessitated, reaching 45° at an albedo of 0.87, where the annual energy rose from 35.212 to 36.999 MWh/yr, signifying a 5.07% increase relative to the reference condition. The results validate that the optimal tilt angle fluctuates with ground-surface albedo, as surface reflectivity affects solar irradiation and energy output. Integrating actual albedo values in photovoltaic models is crucial for precise tilt adjustment and enhanced system efficiency.

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1. INTRODUCTION

Solar energy is widely regarded as a highly promising, renewable energy source that is both abundant and environmentally friendly. Furthermore, it represents a viable energy alternative source. Currently, photovoltaic (PV) systems are the best and most efficient way to harvest the solar energy. These systems have the capability to directly convert irradiation intensity into electrical energy [1]. The maximum output of a PV system panel is achieved when the incident ray is perpendicular to the plane of the panel [2]. The solar energy output of a PV system depends on the amount of solar radiation reaching the arrays [3]. The amount of solar radiation depends on the time of the day and the panel placement where it concerns the sun [4]-[6]. Also, the angle of the PV arrays concerning the horizontal is one of the most critical factors that affect the amount of radiation collected by a fixed PV array. Therefore, PV modules must be tilted at optimal angles to capture the optimum amount of available solar energy at a given location. In most cases, the best tilt angle for a fixed PV array depends on the weather, the location and the seasonal time. Because of this, the best tilt angles for a PV array used all year will be different from one place to another. Until now, many researches have been done on the best tilt angle for PV arrays, and many experimental correlations can be used to predict the best tilt angle [7], [8]. The ground reflector (albedo) and the module's orientation are another factors would affect the amount of solar energy output of the PV array. In the absence of ground albedo measurements, it is common practice to utilize the mean value of 0.2 as a substitute, denoting the reflective characteristics of uncovered ground devoid of snow [9]. Significant resources are spent on designing and modelling solar PV energy systems to achieve maximum output power. Ineichen *et al.* [10] measured ground reflected radiation compared with the value of 0.2, which is proposed by Liu and Jordan for Geneva.

The study's findings suggest that the constant value of 0.2 is excessively high for a geographical situation such as in Geneva. Furthermore, as Ineichen *et al.* [11] asserted, the persistent numerical quantity is deemed inadequate and implausible. Numerous authors have determined optimal tilt angles theoretically, experimentally, and in simulation by calculating the maximum solar irradiation reaching the PV modules. Tuama *et al.* [12] showed that the tilt angle of 30° with a 0° azimuth angle is the best of all the angles for Baghdad city. There is also evidence that small changes in direction (up to 30°) do not affect the performance of PV systems. Hussain *et al.* [13] showed that a 30 fixed tilt angle is optimal, and 0° is the optimal azimuth angle. Obaid *et al.* [14] compared the estimated global efficient solar radiation and calculated radiance for a 30° tilted surface. Both were highest in July and August and lowest in December. Al-Khazzar [15] considered an average tilt angle between 30° and 50° during the summer and winter as the optimum tilt angle. Khadim *et al.* [16] indicated that each province's optimal monthly tilt angle is between 1 and 8 degrees. This information was used in Baghdad, where the optimal tilt was 31°, to get the maximum energy from solar panels each year. The optimal tilt angle in [17] was 31°, according to the maximum yearly power intensity. Kadhim [18] found that optimum tilt angles for winter, spring, summer, autumn, and the year are as follows: 60.41°, 38.88°, 5.26°, 31.34°, and 33.97°. Ahmed *et al.* [19] found that the optimal tilt angle is the same as the latitude of Baghdad. Mahdi and Abdul-Wahid [20] showed that the optimum tilt angle for all days of the year was 35°. Hussein [21] found that since the evaluations were done in winter, the optimum tilt angle for Baghdad should be 49°. Al-Shammari [22] showed that for un-shaded panels, the best tilt angle to get the most sunlight is 60o in December, 5° in June, and somewhere in between in the other months. Ali [23] used a mirror reflector and found that the best azimuth angle for the surface was 36 °E and the optimum degree of tilt for the surface was 60°. Also, the authors found that putting a mirror at the bottom of a solar cell panel at an angle of 120° will increase the output power. Salum *et al.* [24] used a bifacial PV module to investigate the optimum height and tilt angle of bifacial solar cells in Baghdad City at different heights above the ground (100, 120, 140, and 60 cm) and tilt angles (0°, 12°, 30°, 49°, and 70°) for each height. The results showed that, when the height goes from 100 cm to 120 cm, the growth generally levels off at 140 cm and 160 cm. Based on this finding, the best height for a bifacial PV panel in Baghdad is 120 cm. The results additionally indicated that photovoltaics perform best at a tilt of 49°.

The optimal tilt angle for maximizing incident irradiation on the PV arrays depends on the ground albedo, especially when albedo varies rather than remaining constant [25], [26]. Prior research on photovoltaic PV system performance has predominantly concentrated on solar configuration, climatic conditions, and array orientation, while minimally addressing the surface type on which PV modules are installed and its impact on reflected radiation and tilt-angle optimization. Most current models use a constant albedo value of 0.2, hence oversimplifying the variability of ground-surface reflection observed in actual operational contexts. Thus, the true effect of albedo change on the optimal tilt angle and energy output remains inadequately investigated.

This research methodically investigates the correlation between ground-surface albedo and the best tilt angle that maximizes the yearly production of energy of a fixed on-grid photovoltaic system. The analysis commences a reference albedo value of 0.2 and its corresponding optimal tilt of 31° for the climatic conditions of Baghdad, Iraq, subsequently followed by simulations across various albedo values to ascertain how fluctuations in surface reflectivity alter the incident irradiation and power generation.

This study's originality is in quantifying the relationship between albedo variations and tilt-angle optimization through PVsyst simulations. This methodology presents a more realistic and site-specific structure for photovoltaic design, providing critical insights for enhancing the precision of performance forecasting and system optimization across varying surface conditions. The subsequent sections of this work are structured as follows: i) Section 2 delineates the research methodology, encompassing the characterization of the PV system, simulation configuration, and analytical procedure; ii) Section 3 discusses the results and analysis, emphasizing the correlation among albedo, tilt angle, and energy yield; and iii) Finally, section 4 presents the conclusions.

2. RESEARCH METHODOLOGY

Solar energy power is typically calculated based on the irradiation received by the PV array's tilted plane. The theoretical model shows the relationship between albedo and tilt angles, as well as the effect of these angles on irradiation received by PV modules. The Perez model in PVsyst software is used to simulate the amount of irradiation that reaches the PV arrays. System designers require values for solar irradiation on such tilted panels; however, measured or approximated irradiation data are primarily available for surfaces with normal incidence or horizontal orientation. Therefore, it is necessary to convert these data into irradiation on inclined surfaces.

2.1. Tilt angle and albedo

A flat surface absorbs solar irradiation in three ways, as shown in (1) [27], [28].

$$G_t = G_B + G_D + G_G \tag{1}$$

Where: G_B is the beam irradiation, G_D is the diffuse irradiation, and G_G is the ground-reflected irradiation. From Figure 1, the tilted surface beam irradiation (G_{Bt}) is (2).

$$G_{Bt} = G_{Bn} cos\,(\theta) \tag{2}$$

In addition, the horizontal surface beam irradiation (G_{Bh}) is (3).

$$G_{Bh} = G_{Bn}\, cos\, cos\,(\phi) \tag{3}$$

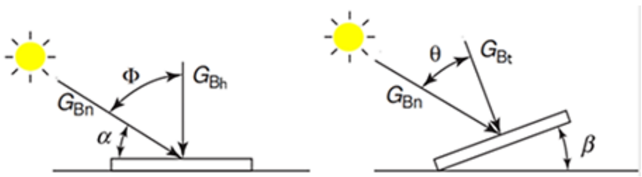

Figure 1. Beam irradiation on the horizontal and tilted surfaces

The expression used in general to incidence angle is (4).

$$cos\,\theta = sin\,L\,sin\,\delta\,cos\,\beta - cos\,L\,sin\,\delta\,sin\,\beta\,cos\,Z_s + cos\,L\,cos\,\delta\,cos\,h\,cos\,\beta + sin\,L\,cos\,\delta\,cos\,h\,sin\,\beta\,cos\,Z_s + cos\,\delta\,sin\,h\,sin\,\beta\,sin\,Z_s \tag{4}$$

Where θ: Incidence angle, ϕ : zenith angle, β : tilt angle, Z_s azimuth angle, h: Hour angle, δ : Declination, and α: Solar altitude angle. For the horizontal surfaces, θ = ϕ , $\beta = 0$, substitute in (4).

$$cos(\phi) = \sin L \sin\delta + \cos L \cos\delta \cos h \tag{5}$$

The beam irradiation tilt factor is (6).

$$R_B = \frac{G_{Bt}}{G_{Bh}} = \frac{cos\,(\theta)}{cos\,(\phi)} \tag{6}$$

For any surface beam irradiation is (7).

$$G_{Bt} = R_B G_{Bh} \tag{7}$$

According to the isotropic sky model, diffuse irradiation on the horizontal surface is calculated as (8) and (9).

$$G_D = 2\int_0^{\pi/2} G_R\, cos(\Phi)\, d\Phi = 2G_R \tag{8}$$

$$G_R = \frac{G_D}{2} \tag{9}$$

Where G_R: diffuse sky irradiance (W/m^2 *rad*). Diffuse irradiation on tilted is (10).

$$G_{D_t} = \int_0^{\frac{\pi}{2}-\beta} G_R \cos\Phi \, d\Phi + \int_0^{\frac{\pi}{2}} G_R \cos\Phi \, d\Phi \quad (10)$$

Substitute in (9) and (10):

$$G_{D_t} = G_D \left[\frac{1+cos(\beta)}{2}\right] \quad (11)$$

Similarly, the ground-reflected irradiation is expressed as G_G is $\rho_G(G_B + G_D)$, which pertains to the reflectivity of the ground with respect to isotropic ground reflected radiation (G_t) [27], [29], [30].

$$\rho_G(G_B + G_D) = 2\int_0^{\frac{\pi}{2}} cos\, G_r \cos(\Phi)\, d\Phi = 2G_r \quad (12)$$

On a tilted surface (13).

$$G_{G_t} = \int_{\frac{\pi}{2}-\beta}^{\frac{\pi}{2}} cos\, G_r cos\,(\Phi)\, d\Phi \quad (13)$$

From (12) and (13) the ground reflected will be:

$$G_{G_t} = \rho_G(G_B + G_D)\left[\frac{1-cos\,(\beta)}{2}\right] \quad (14)$$

Where ρ_G: represents the ground albedo. Substitute (10) and (13) in (6), then (16).

$$G_t = R_B G_B + G_D\left[\frac{1+cos\,(\beta)}{2}\right] + (G_B + G_D)\rho_G\left[\frac{1-cos\,(\beta)}{2}\right] \quad (15)$$

The global horizontal irradiation (G) is the total of the direct radiation and the diffuse irradiation incident on the horizontal plane.

$$G = G_B + G_D \quad (16)$$

The (15) may be written as (17).

$$R = \frac{G_t}{G} = \frac{G_B}{G} R_B + \frac{G_D}{G}\left[\frac{1+cos\,(\beta)}{2}\right] + \rho_G\left[\frac{1-cos\,(\beta)}{2}\right] \quad (17)$$

Where R is tilt factor total radiation. From, (17) the tilt factor of ground reflected is (18).

$$R_{Gt} = \rho_G\left[\frac{1-cos\,(\beta)}{2}\right] \quad (18)$$

The tilt factor for diffuse irradiation is (19).

$$R_D = \left[\frac{1+cos\,(\beta)}{2}\right] \quad (19)$$

2.2. Tilted angle and PV module

Most solar energy may be collected from tilted surfaces. The tilt is also affected by the time of year and latitude. At midday in September and March, the radiation from the sun is going to be perpendicular to the surface of the collector if the angle at which it tilts is equal to the latitude. In the summer, when sun radiation is at its strongest, it is helpful to angle the surface slightly away from vertical. However, for the maximization in the winter, the surface must tilt further to the vertical. Tilt and orientation don't have a huge impact. In this research, it was taken into account that the angle is fixed throughout the year, and for the purpose of increasing solar radiation and the energy output from the system, the effect of the ground reflector on the optimum tilt angle that achieves the maximum output power was studied. This will be cheaper than using a solar tracker for the purpose of changing the angle every month. With the help of Figure 2, it can easily calculate the solar altitude angle N at solar noon, which is a crucial solar parameter [28]. The altitude angle refers to the angular distance between the sun and the horizon located directly beneath it at a given location. The relationship depicted in Figure 3 can be expressed as (20).

$$\beta_N = (90^0) - L + \delta \tag{20}$$

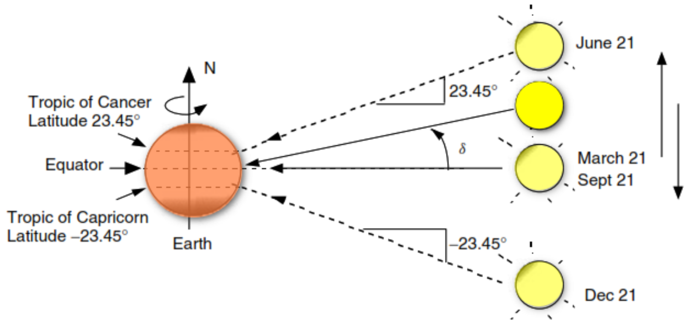

Figure 2. Different view for the earth and sun

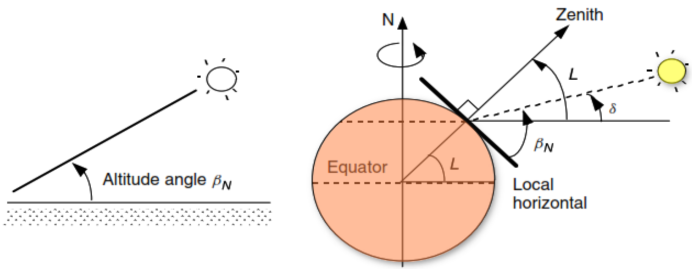

Figure 3. The solar noon altitude angle about the sun

2.3. Simulation model method

PVsyst offers Hay's and Perez transposition models that can be used to find the world incidence of radiation on a tilted plane. [29]. The two models come up with different ways to figure out the scattered parts of the radiation that hits the tilting plane. According to the Hay model, diffuse irradiance is made up of an isotropic input and a "circumsolar" component that is equal to the beam component. [30]. The "horizon band" that the Perez-Ineichen model adds is another scattered part. [31]. It divides the sky into sections and figures out how the circumsolar and horizon bands change by comparing data from more than two dozen measurement sites around the world. Because of that and based on [32], Perez model is more accurate than the Hay model. Therefore, this study uses the Perez transposition model. Transposition refers to the method of determining the incident irradiance on a tilted plane based on available horizontal irradiance data [29]. The PVsyst is utilized to convert the global horizontal irradiation (GlobHor) to the global incident irradiation in the collector plane (GlobInc) for any given tilt angle. From (6), the beam radiation tilt factor, which is equal to the tilted surface beam irradiation over the horizontal surface beam irradiation, and the definition of transposition models or transposition factor (TF) in simulation, which is equal to (21).

$$\text{TF} = \frac{GlobInc}{GlobHor} \tag{21}$$

The tilt factors and transposition factor determine the best tilt orientation. The important parameters of the simulation depend on global incident irradiation in the collector plane (GlobInc) because the global horizontal irradiation (GlobHor) is constant in the same location.

2.4. Simulation methodology

2.4.1. Set geographical coordinates

This research designs and simulates an on-grid PV system location in Baghdad, Iraq, with the coordinates at 33.31 N°, 44.38 E° and 30 m above sea level. Geographic coordinates from PVsyst software, as shown in Figure 4, provide meteorological data. Yearly horizontal global sun irradiance (GlobH) and diffuse component (DiffH) are shown in Table 1.

Table 1. Yearly horizontal global and diffuse irradiance in Baghdad

Parameter	GlobH	DiffH
Values	kWh/m²	kWh/m²
Yearly value	1833.9	554.7

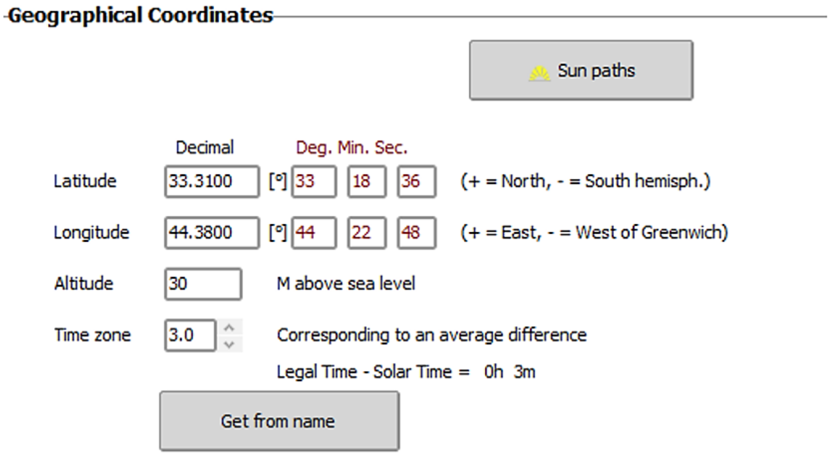

Figure 4. Geographical coordinates in PVsyst for Baghdad city

2.4.2. The orientation of the PV panel

PVsyst calculates the annual optimal tilt angle for fixed tilted plane in the orientation stage. Baghdad should tilt at 30° and 0º Azimuth as shown in Figure 5 with albedo (0.2), and PV panels face south. Upon conducting numerous tilt angle tests, the simulation results indicate that the angle yielding the maximum output power differs from the angle previously assumed.

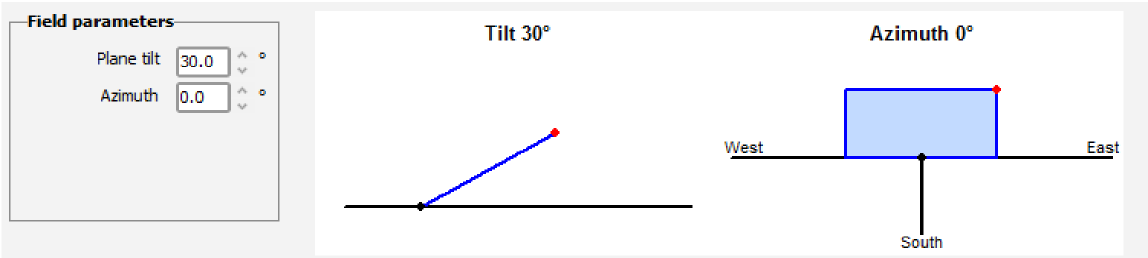

Figure 5. Set the tilt angle

2.4.3. System description

The photovoltaic system considered in this research is a grid-connected system with 20.48 kWp power. It contains 64 modules (4 strings × 16 in series); the normal power of one module is 320 Wp, and the module area is 124 m^2. The other PV system characteristics are shown in Table 2.

2.4.4. Effect of ground albedo on the optimal tilt angle of PV panels

The ground for installing solar systems may be concrete, sand, White Portland cement, snow, and each of these grounds has a special albedo value. In this research, six PV system-mounting surfaces were tested in the simulation by selecting the appropriate albedo value for each surface. The value of albedo for each type of ground is as listed in [33], [34]. Increases in tilt angle will be made if the surface albedo value exceeds the constant albedo value (0.2). If the surface's albedo is less than the reference level of 0.2. Then, the tilt angle will gradually decrease until the maximum of the global incident in the collector plane (GlobInc) and the energy injected into the grid (E_Grid) are reached [25]. The type of mounting surfaces used in this research is shown in Table 3.

Table 2. Grid-connected system characteristics

Item	Parameters	Value /Description
PV module	Manufacturer	Phono Solar
	Model	PS320P-24/T Maxim
	Unit Nom. Power	320 Wp
	Number of PV modules	64
	Nominal (STC)	20.48 kWp
	Modules	4 Strings x 16 in series
	Nominal (STC)	20 kWp
	Total	64 Modules
	Module area	124 m²
Inverter	Manufacture	Trannergy
	Model	TRN020KTL
	Unit Nom. Power	20.0 kWac
	Number of inverters	2 * MPPT 50% 1 unit
	Total power	20.0 kWac
PVsyst database	Operating voltage	250-800 V
	Pnom ratio (DC:AC)	1.02

Table 3. Surface albedo used in the study [33], [34]

Surface	Average Albedo
Sand, dry	0.180
Sand, wet	0.090
Concrete	0.250
Coal fly ash	0.620
White paint	0.700
White Portland cement	0.870

3. RESULTS AND DISCUSSION

In this research, the influence of several factors on the performance of photovoltaic PV modules has been considered, such as global incident irradiation in the collector plane (GlobInc), effective energy at the output of the array (EArray) and energy injected into the grid (E_Grid). The global horizontal irradiation is considered constant in this location. For obtaining research results, the following steps were applied:

i) Step 1: Obtain the yearly fixed optimal tilt angle

PV Syst software suggests 30° as the annual optimum tilt angle with constant albedo (0.2). In this angle, the yearly results showed that (GlobInc) is 2054.2 kWh/m², Effective energy at the output of the array (E_Array) and the (E_Grid) is 35.913 MWh, 35.209 MWh, respectively. The 30° angle then decreased or increased to increase these values. Table 4 shows a comparison between two tilt angles, a 30° and a 31°. At a 31° tilt angle, the GlobInc is lower than that when the tilt angle was 30°, but the value of E_Array and E_Grid is still a higher value that is, because the PV losses due to temperature at tilt angle 30° is 11.811%, which is more than the losses at a tilt angle of 31° which is equal to 11.796%.

Table 4. Yearly horizontal global, incidence irradiance and the energy output of the system

Tilt angle	GlobHor kWh/m²	GlobInc kWh/m²	EArray MWh	E_Grid MWh
29	1833.9	2053.9	35.902	35.199
30	1833.9	2054.2	35.913	35.209
31	1833.9	2054.0	35.916	35.212
32	1833.9	2053.2	35.910	35.205
33	1833.9	2052.0	35.895	35.190

ii) Step 2: different surface albedo with yearly variables fixed tilt angle

Different surface albedo, as in Table 3, will be taken, and the result for each case. For each case in this study, as in step 1, the reference annual optimum tilt angle is at 30° with constant albedo (0.2), and the comparison will be according to reference annual optimum tilt angle results as in Table 4. If the surface albedo value less than constant albedo (0.2) the procedure will be starting at reference annual optimum tilt angle then decreased or increased reference annual optimum tilt angle until reaching maximum results of (EArray, E_Grid). The procedures are summarized in the flow chart shown in Figure 5. As in Table 3, there are two values (0.09, 0.18) less than (0.2). The results are shown in Table 6 and Table 6 for albedo values 0.18 and 0.09. As shown in Table 5 the maximum results of (EArray, E_Grid) achieved at tilt angle 30.5°, which means that at an albedo value of 0.18, the optimum tilt angle is at a 30.5°. Similarly, for surface albedo of 0.09, the main results, as shown in Table 6, the maximum results of (EArray, E_Grid) are achieved at tilt angle 29°.

According to Table 3, there are four values more than the constant albedo value of 0.2. Firstly, the values of GlobInc, EArray, E_Grid are measured for each albedo value and according to fixed reference annual optimum tilt angle which is 31° for this case, as shown Table 7. Secondly, the procedure will start at the reference annual tilt angle (31°), then increase or decrease this reference annual tilt angle. The final annual optimum tilt angle with different surface albedo will be the one that achieves maximum results of (GlobInc, EArray, E_Grid). The optimum tilt angles for each albedo value above 0.2 are as shown in Table 8. Finally, the optimum tilt angle, which gives maximum energy injection into the grid for each type of ground albedo for this study are summarized in Figure 7.

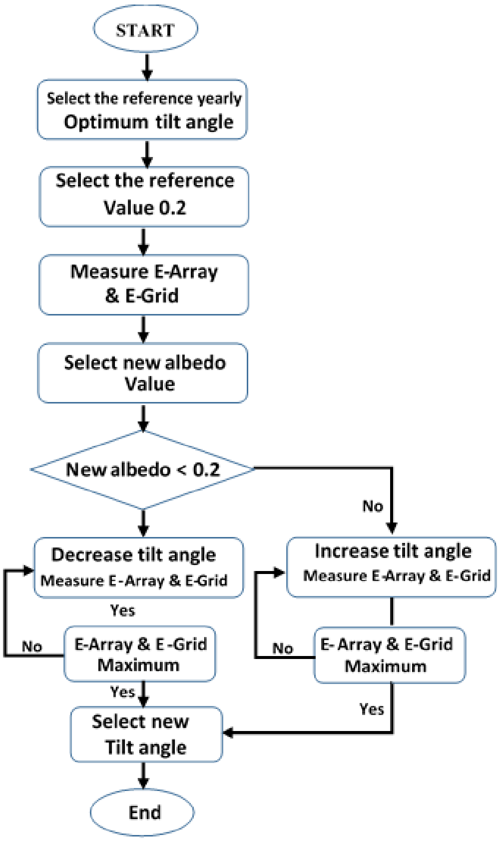

Figure 6. Optimal tilt angle selecting procedures

Table 5. Energy values and incidence radiation albedo value (0.18) with respect to albedo value (0.2)

Tilt angle Degree	Albedo Value	GlobInc kWh/m²	EArray MWh	E_Grid MWh
33	0.18	2049.0	35.852	35.148
32	0.18	2050.4	35.869	35.166
31	0.18	2051.3	35.878	35.175
30.5	0.18	2051.6	35.879	35.176
30	0.18	2051.7	35.878	35.175
29	0.18	2051.6	35.870	35.167

Table 6. Energy values and incidence radiation for surface albedo (0.09) with respect to albedo value (0.2)

Tilt angle Degree	Albedo Value	GlobInc kWh/m²	EArray MWh	E_Grid MWh
32	0.09	2037.9	35.688	34.987
31	0.09	2039.5	35.708	35.007
30	0.09	2040.7	35.719	35.019
29	0.09	2041.2	35.721	35.021
28	0.09	2041.3	35.715	35.015

Table 7. Energy values and incidence radiation for different albedo values with respect to tilt angle (31°)

Tilt angle Degree	Albedo Value	GlobInc kWh/m²	EArray MWh	E_Grid MWh
31	0.25	2060.5	36.010	35.304
31	0.620	2109.0	36.705	35.986
31	0.700	2119.4	36.854	36.133
31	0.870	2141.7	37.171	36.444

Table 8. Final annual optimum tilt angle for different surface albedo

Tilt Angle Degree	Albedo Ratio	GlobInc kWh/m²	EArray MWh	E_Grid MWh
31.5	0.250	2060.4	36.011	35.305
38	0.620	2119.7	36.889	36.166
40	0.700	2131.7	37.069	36.341
45	0.870	2177.4	37.739	36.999

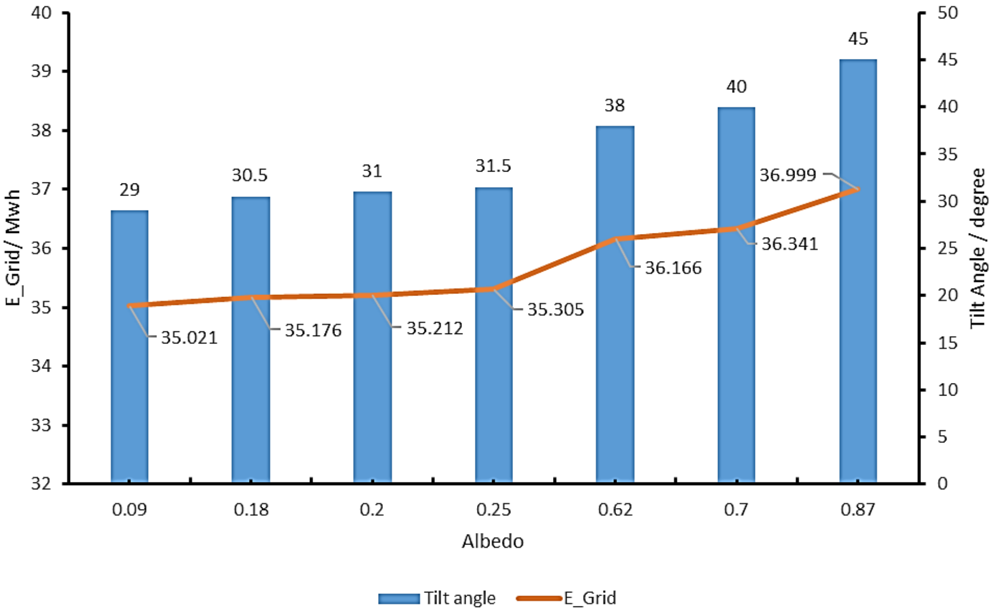

Figure 7. The types ground albedo versus optimum tilt angle and energy injection into the grid

4. DISCUSSION

The simulation results in Tables 5–8 indicate a significant correlation among ground-surface albedo, tilt angle, and the energy performance metrics of the PV system, specifically (GlobInc), (EArray), and (E_Grid). In the reference scenario (albedo = 0.2, tilt = 31°), the GlobInc attained roughly 2054 kWh/m², resulting in EArray = 35.916 MWh and E_Grid = 35.212 MWh/yr. As the albedo diminished to 0.18 (Table 5) and 0.09 (Table 6), the optimal tilt angles yielding the maximum E_Grid adjusted to 30.5° and 29°, respectively. The diminished ground reflectivity resulted in a marginal decline in the diffuse-reflected radiation component; yet, reducing the tilt angle enhanced the capture of direct solar radiation, preserving an energy output of around 35.17–35.02 MWh/yr. This trend indicates that, in low-albedo conditions, a reduced tilt angle is beneficial for optimizing direct solar gain.

Conversely, when the albedo went above 0.2 (Tables 7–8), the ground exhibited higher reflectivity, contributing to a greater upward radiation portion that favored steep module orientations. Consequently, GlobInc experienced a gradual increase from 2060.4 kWh/m² at an albedo of 0.25 to 2177.4 kWh/m² with an albedo of 0.87. The optimal tilt angle increased from 31.5° to 45°, while E_Grid climbed from 35.305 MWh to 36.999 MWh, resulting in a total improvement of 5.07% relative to the reference scenario.

This distinct pattern demonstrates the physical dependence of photovoltaic performance on tilt angle and surface reflectivity. As GlobInc experiences an increase in albedo and modified tilt, both the EArray and E_Grid exhibit a corresponding rise, confirming that the incident irradiation on the collector plane is the primary determinant of energy gain. The optimum tilt angle is not a constant specific to a location but must be ascertained based on the actual ground albedo, ensuring that the modules maximize the capture of both direct and reflected solar radiation for enhanced yearly energy production.

Future studies should be focus on developing local design guidelines that link climatic conditions with optimal tilt albedo arrangement for PV systems. Subsequent studies should include bifacial PV modules and integrate a comprehensive techno-economic analysis in accordance with the IEC 62548, IEC 61730, and IEC 61215 standards.

5. CONCLUSION

This study evaluated the impact of ground-surface reflection (albedo) on optimum tilt angle and energy output of a stationary on-grid photovoltaic PV system situated in Baghdad, Iraq. The investigation demonstrated a direct and constant relationship between albedo and the tilt angle that optimizes annual energy output.

The results indicated that as the albedo lowers below the reference value (0.2), the optimal tilt angle marginally reduces to sustain maximum energy capture. In contrast, as the albedo reaches 0.2, the optimal tilt angle incrementally increases from 31.5° at an albedo of 0.25 to 45° at 0.87 leading to enhanced reflected irradiation and a potential annual energy gain of up to 5.07% relative to the reference situation. The study suggests that each surface type with a different albedo possesses a specific tilt configuration that optimizes system efficiency.

Consequently, assuming a fixed tilt angle regardless of the surrounding surface reflection may result in inferior photovoltaic performance. Incorporating actual albedo values into photovoltaic design and simulation tools, such as PVsyst, is crucial for precise tilt-angle assessment and dependable energy prediction. This research underscores the necessity for future studies to incorporate the temporal variation of albedo (e.g., resulting from seasonal changes, dust accumulation, or ground cover) to improve forecast accuracy and system optimization in real operating settings.

FUNDING INFORMATION

Authors state no funding involved.

AUTHOR CONTRIBUTIONS STATEMENT

This journal uses the Contributor Roles Taxonomy (CRediT) to recognize individual author contributions, reduce authorship disputes, and facilitate collaboration.

Name of Author	C	M	So	Va	Fo	I	R	D	O	E	Vi	Su	P	Fu
Ahmed Daud Mosheer	✓	✓				✓	✓	✓	✓		✓	✓		
Ahmed H. Duhis	✓	✓	✓		✓			✓		✓		✓	✓	
Hussain A. Hammas		✓	✓	✓	✓				✓	✓				✓

C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
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 authors confirm that the data supporting the findings of this study are available within the article.

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