



# Optimization of Fixed and Seasonal Tilt Angles for Photovoltaic Systems under Clear-Sky Conditions

Shivan Shkur Mahmood <sup>a\*</sup>, Alaa M. Abdulrahman <sup>a</sup>, Ghamgeen I. Rashed <sup>b</sup>

<sup>a</sup>Department of Electrical Engineering, College of Engineering, University of Sulaimani, Sulaymaniyah, Iraq.

<sup>b</sup>School of Electrical Engineering and its Automation, Wuhan University, Wuhan, China.

Submitted: 05 July 2026

Revised: 19 September 2026

Accepted: 28 September 2026

## \* Corresponding Author:

[shivan.mahmood@univsul.edu.iq](mailto:shivan.mahmood@univsul.edu.iq)

**Keywords:** Photovoltaic systems, Solar energy, Tilt-angle optimization, Clear-sky conditions, Renewable energy.

**How to cite this paper:** S.S. Mahmood, A. M. Abdulrahman, G. I. Rashed, "Optimization of Fixed and Seasonal Tilt Angles for Photovoltaic Systems under Clear-Sky Conditions", KJAR, vol. 11, no. 2, pp. 121-133, December 2026, doi: 10.24017/science.2026.2.6



Copyright: © 2026 by the authors. This article is an open access article distributed under the terms and conditions of the Creative Commons Attribution (CC BY-NC-ND 4.0)

**Abstract:** This study investigates the optimal fixed and seasonal tilt angles for photovoltaic systems in Sulaymaniyah, Iraq, under clear-sky conditions. A mathematical model based on solar geometry was developed to estimate annual solar irradiation, and the generalized reduced gradient nonlinear optimization method was used to determine the optimal fixed and seasonal tilt angles. Annual fixed, biannual, quarterly, and monthly tilt-angle strategies were compared to identify the most suitable approach for maximizing annual solar irradiation. For each strategy, the model simulated the annual irradiation received by the panels and identified the tilt angles that maximized this value. The annual analysis identified a fixed tilt angle of approximately 34° as the optimal year-round setting. A biannual adjustment strategy, using tilt angles of 10° in summer and 55° in winter, provided a practical and efficient alternative to conventional fixed installations. Its annual irradiation was comparable to that achieved through quarterly and monthly adjustments, with differences of only approximately 1–2%. The additional irradiation gained through more frequent adjustments was therefore relatively small compared with the biannual approach. These results indicate that two adjustments per year offer a practical balance between irradiation gains and adjustment frequency under the modeled conditions. The findings demonstrate the value of selecting appropriate tilt angles to maximize the annual solar irradiation received by photovoltaic panels and provide practical guidance for the design and optimization of photovoltaic systems in Iraq and regions with similar climates.

## 1. Introduction

Fossil fuels remain the world's largest source of energy. However, concerns about environmental sustainability, the depletion of fossil fuel resources, and rising energy costs have accelerated the development of renewable energy technologies worldwide [1, 2]. Solar energy is one of the most abundant and promising renewable energy sources. The increasing installation of stand-alone and hybrid photovoltaic (PV) systems, together with declining renewable electricity generation costs, has supported the global expansion of solar energy [3, 4]. Despite Iraq's considerable solar energy potential, particularly in northern regions such as Sulaymaniyah, this resource remains largely underutilized, providing substantial opportunities for the wider deployment of PV technologies. PV cells convert solar radiation directly into electricity through the photovoltaic effect. The panel tilt angle relative to the horizontal plane strongly influences the amount of solar radiation received and the electrical power generated [5]. Selecting an appropriate tilt angle is therefore important for maximizing incident solar irradiation and improving PV energy yield. Although solar tracking systems continuously adjust panel orientation to maximize solar radiation capture, they increase system complexity, maintenance requirements, and installation costs. Optimizing fixed tilt angles and introducing periodic tilt-angle adjustments therefore remain effective and economical approaches to improving PV system performance [6].

Iraq receives approximately 2,800–3,300 hours of sunshine annually, with solar irradiation of approximately 6.5–7.0 kWh/m<sup>2</sup> [7]. Sulaymaniyah, in northeastern Iraq, also has considerable potential for solar energy applications. However, electricity generation remains dominated by fossil-fuel-based power plants. Increasing the contribution of renewable energy is therefore essential for reducing environmental impacts and improving energy sustainability. Optimizing PV panel tilt angles to maximize incident solar irradiation offers a practical means of improving annual energy production and system efficiency [8]. Numerous international studies have demonstrated that optimal panel tilt angles depend strongly on geographical location and local climatic conditions. Benghanem [9] investigated optimal tilt angles for solar panels in Madinah, Saudi Arabia, while Skeiker [10] examined solar collectors under Syrian climatic conditions. Daut *et al.* [11] conducted a similar study in Perlis, Malaysia. These studies demonstrate the importance of selecting tilt angles for specific locations. Duffie and Beckman [1] described the relationship between the angle of incidence and the radiation received by a tilted surface, while Mousazadeh *et al.* [2] discussed practical aspects of tracking and fixed PV systems. Several studies have also examined optimal tilt angles in Iraq. Zurfi *et al.* [12] investigated optimal PV tilt angles, orientations, and tracking configurations under Iraqi weather conditions. Taha and Hameed [13] examined optimal panel tilt angles based on solar radiation in Duhok, and Ali [14] estimated optimal tilt angles for PV panels in several Iraqi cities.

In addition to analytical and location-specific approaches, researchers have used optimization algorithms to determine optimal PV tilt angles. In China, the harmony search algorithm was used with a Julian day model to optimize module tilt and azimuth angles. Monthly tilt-angle adjustments maximized annual solar irradiation while maintaining a south-facing orientation [15]. Al-Shammari *et al.* [16] investigated optimal tilt angles and experimentally evaluated a stand-alone PV system in Baghdad. Shariah *et al.* [17] optimized solar collector tilt angles, while Kaddoura *et al.* [18] examined solar radiation and optimal PV panel tilt angles in Saudi Arabia. More recent research has investigated fixed, seasonal, and adaptive tilt-angle optimization using various radiation models and optimization methods. Ashetehe *et al.* [19] developed seasonal and annual tilt-angle models using isotropic and anisotropic diffuse-radiation models. Melhem and Shaker [20] examined optimal PV tilt angles and solar radiation across the Gulf Cooperation Council region. Tamoor *et al.* [21] compared isotropic and anisotropic radiation models at several locations and highlighted the importance of location-specific tilt-angle optimization for maximizing PV performance. Liu *et al.* [22] combined ground-based and satellite-derived solar radiation data to estimate optimal tilt angles, demonstrating the influence of geographical and climatic variations. Abdelaal and El-Fergany [23] evaluated different tilt-angle adjustment methods and provided experimental validation. Lu and Qin [24] examined the temporal variability of solar resources and optimized tilt angles using long-term hourly surface solar radiation data. Teyabeen and Mohamed [25] investigated optimal PV tilt angles under Libyan climatic conditions, while Ibrahim and Aljanabi [26] examined the influence of tilt angle on PV output in Iraq. Despite this research, studies in Iraq have primarily focused on other locations or annual fixed-angle optimization. Few have provided a detailed comparison of seasonal and multiple-adjustment strategies for Sulaymaniyah under clear-sky conditions.

The present study therefore investigates optimal fixed and seasonal PV tilt angles in Sulaymaniyah under clear-sky conditions without clouds or aerosols. Solar geometry was used to model and simulate the effects of different tilt-angle configurations on annual irradiation received by PV panels. This study provides the first systematic comparison of annual fixed, biannual, quarterly, monthly, and multiple-adjustment strategies for Sulaymaniyah within a consistent clear-sky framework, whereas previous studies have examined Baghdad, Basrah, and Duhok. Its principal contribution is an evaluation of the trade-off between annual irradiation gains and the number of tilt-angle adjustments, providing a practical basis for selecting an adjustment strategy.

The remainder of the paper is organized as follows: Section 2 describes the solar geometry and irradiance model, the simulation setup, and the tilt-angle optimization strategies. Section 3 presents the simulation results, and section 4 discusses them in relation to previous studies. Section 5 summarizes the conclusions, limitations, and directions for future research.

## 2. Materials and Methods

The methodology comprised four stages. First, solar geometry and clear-sky irradiance for Sulaymaniyah were calculated using the equations presented in section 2.1. Second, different panel tilt-angle configurations were evaluated over a full year. Third, the generalized reduced gradient (GRG) nonlinear optimization method was used to determine optimal annual and seasonal tilt angles. Finally, the annual irradiation achieved using different adjustment strategies was compared with the number of adjustments required.

### 2.1. Solar Geometry and Irradiance Modeling

PV system performance depends strongly on the solar radiation incident on the panel surface. The amount received is determined by the geometric relationship between the sun's position and the panel orientation [27]. Accurate modeling of solar angles and irradiance is therefore important for determining optimal panel tilt angles.

The solar declination angle ( $\delta$ ) is the angle between the sun's rays and the Earth's equatorial plane. The tilt of the Earth's axis and its orbit around the sun cause this angle to vary seasonally between  $-23.45^\circ$  and  $+23.45^\circ$  [28]. The declination angle is calculated as follows:

$$\delta = 23.45^\circ \times \sin\left(\frac{2\pi(n + 284)}{365}\right) \quad (1)$$

where  $n$  is the day of the year, with  $n = 1$  corresponding to January 1. Figure 1 illustrates the declination angle [28].

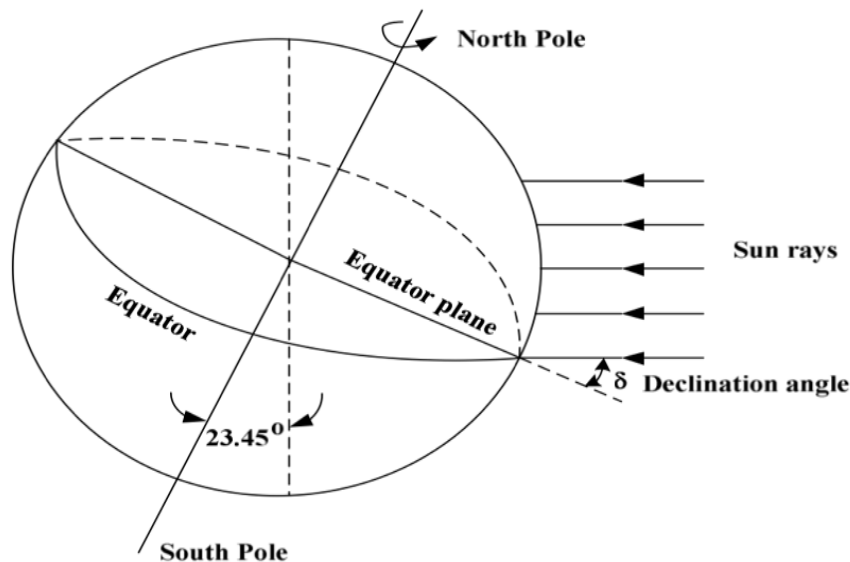


Figure 1: Solar declination angle [28].

The solar hour angle ( $\omega$ ) describes the sun's angular displacement east or west of the local meridian [28]. It is calculated as follows:

$$\omega = (\text{Time in hours from 12 PM}) \times 15^\circ \quad (2)$$

The sunrise/sunset hour angle ( $\omega_s$ ) describes the sun's angular position at sunrise and sunset. Its annual variation determines the duration of daylight [28]. It is calculated as follows:

$$\omega_s = \cos^{-1}(-\tan(\delta) \times \tan(\varphi - \beta)) \quad (3)$$

Several geometric parameters describe the relationship between the sun's position and PV panel orientation. These parameters, illustrated in figure 2, are required for modeling incident solar irradiance [28–30]:

$\beta$  (tilt angle): The angle between the panel surface and the horizontal plane. This is the principal variable optimized in this study to maximize annual irradiation received by the panel.

$\gamma$  (orientation angle): The panel azimuth angle measured relative to true south. A south-facing orientation was assumed in all simulations; therefore,  $\gamma = 0^\circ$ .

$\varphi$  (latitude): The geographical latitude of the installation site. Sulaymaniyah, Iraq, is located at approximately  $35.57^\circ$  N [31].

$\theta$  (angle of incidence): The angle between the sun's rays and the normal to the panel surface.

$\theta_0$  (zenith angle): The angle between the sun's rays and the vertical direction.

Together, these parameters define the geometric relationship between the sun and the PV panel, allowing the incident solar irradiance to be estimated [28–30].

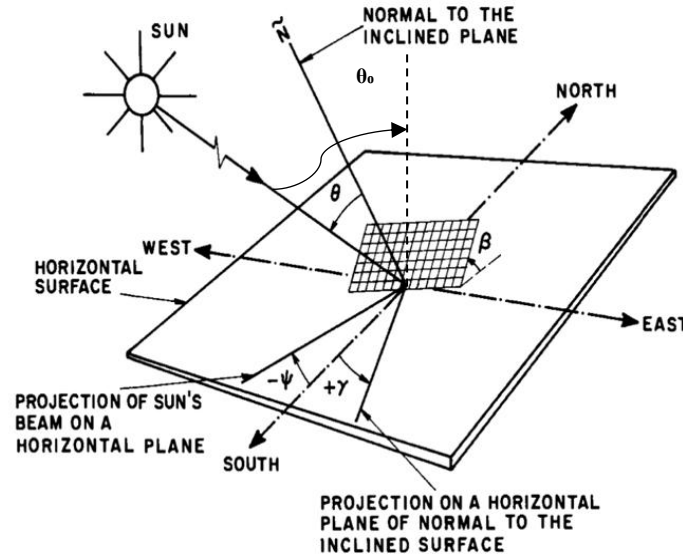


Figure 2: Solar geometry and orientation parameters of a tilted PV panel [28–30].

The angle of incidence ( $\theta$ ) is determined using the general expression presented in the study by Muslim [30]:

$$\cos(\theta) = (\sin\varphi \cos\beta - \cos\varphi \sin\beta \cos\gamma) \sin\delta + (\cos\varphi \cos\beta + \sin\varphi \sin\beta \cos\gamma) \cos\delta \cos\omega + \cos\delta \sin\beta \sin\gamma \sin\omega \quad (4)$$

Equation (4) was simplified for the conditions considered in Sulaymaniyah. The panel tilt angle ( $\beta$ ) was held constant within each optimization period and optimized to maximize annual or seasonal solar irradiation. All panels were assumed to face true south. Substituting  $\gamma = 0^\circ$  into equation (4) gives:

$$\cos(\theta) = \sin\delta \sin(\varphi - \beta) + \cos\delta \cos(\varphi - \beta) \cos\omega \quad (5)$$

This simplified expression was used to estimate irradiance received by PV panels under the clear-sky conditions considered in this study. The model considers only direct-beam radiation and neglects diffuse and ground-reflected components [28–30]. This simplification should be considered when interpreting the resulting optimal tilt angles, particularly when applying them under actual atmospheric conditions. Direct-beam irradiance is calculated as follows:

$$I_B = I_0 \times e^{(-\tau \times AM)} \quad (6)$$

where:

$I_0$  is the extraterrestrial solar irradiance ( $\text{W}/\text{m}^2$ ) and is calculated as follows:

$$I_0 = 1367 \times \left(1 + 0.033 \times \cos\left(\frac{2\pi n}{365}\right)\right) \quad (7)$$

$\tau$  is the atmospheric optical depth, which describes the attenuation of solar radiation as it passes through the atmosphere.

AM is the air mass coefficient, which represents the relative optical path length through the atmosphere.

## 2.2. Simulation Setup

A numerical evaluation based on solar geometry was conducted using the mathematical model developed for this study. The model was implemented computationally to calculate incident solar irradiation under different panel tilt-angle configurations. Optimal tilt angles were determined using the GRG nonlinear optimization algorithm. The simulations assumed ideal clear-sky conditions and excluded the effects of clouds and atmospheric aerosols. These conditions were selected to isolate the influence of panel tilt angle from weather-related variations in incident solar irradiance, allowing a consistent comparison of the adjustment strategies. Values of  $\cos(\theta)$  were calculated for the different configurations and used to estimate annual irradiation incident on the panels.

## 2.3. Tilt-angle Scenarios

Three scenarios were investigated to identify the optimal tilt-angle configuration:

- An annual fixed tilt angle between  $0^\circ$  and  $90^\circ$ , maintained throughout the year.
- Biannual adjustment, with one adjustment in summer and another in winter.
- Multiple-adjustment strategies involving 3–66 tilt-angle changes per year.

Seasonal performance was also evaluated for winter, spring, summer, and autumn. Optimal tilt-angle ranges were identified for each season and used to develop seasonal adjustment strategies.

## 2.4. Performance Evaluation Criteria

Incident solar irradiance was integrated over daily, seasonal, and annual periods to compare the tilt-angle strategies. Two reference configurations were considered: a horizontal installation ( $\beta = 0^\circ$ ) and a conventional fixed tilt angle of  $30^\circ$ . Annual irradiation was calculated for each configuration, and the optimal tilt angle was identified as the angle that maximized this value. Annual irradiation and the corresponding gains relative to the reference configurations were the principal performance indicators.

## 2.5. Tilt-angle Optimization Procedure

Optimal fixed and seasonal tilt angles were determined numerically. First, the solar geometry equations in section 2.1 were used to calculate daily extraterrestrial solar irradiation on a tilted surface for each day of the year. Calculations were repeated at  $1^\circ$  increments over a tilt-angle range of  $0^\circ$ – $90^\circ$  to construct a database of daily irradiation as a function of day of the year and panel tilt angle. Daily irradiation at each tilt angle was calculated using equation (7). Seasonal irradiation was then obtained by summing the daily values for the relevant season:

$$I_{season}(\beta) = \sum_{n=1}^{N_s} I_{daily}(n, \beta) \quad (8)$$

where  $N_s$  is the number of days in the selected season,  $I_{daily}(n, \beta)$  is the daily solar irradiation on day  $n$  for a panel tilt angle  $\beta$  and  $I_{season}(\beta)$  is the total solar irradiation accumulated over the season. Annual irradiation at each tilt angle was calculated by summing the daily values over the year:

$$I_{annual}(\beta) = \sum_{n=1}^{365} I_{daily}(n, \beta) \quad (9)$$

For the fixed-angle configuration, annual irradiation was compared across all evaluated angles, and the angle producing the highest annual value was selected:

$$I_{annual,opt} = \max I_{annual}(\beta) ; 0^\circ \leq \beta \leq 90^\circ \quad (10)$$

The irradiation database was then used to optimize tilt angles for different adjustment periods. Six strategies were evaluated:  $\beta_1$ ,  $\beta_2$ ,  $\beta_3$ ,  $\beta_4$ ,  $\beta_{12}$ , and  $\beta_{66}$ , corresponding to one, two, three, four, twelve, and

sixty-six tilt-angle settings per year, respectively. In the  $\beta_{66}$  strategy, the angle was changed in  $1^\circ$  increments as required to maximize irradiation. The tilt angle assigned to each adjustment period was treated as an optimization variable. The GRG nonlinear optimization algorithm was selected because the panel tilt angle was a continuous decision variable bounded between  $0^\circ$  and  $90^\circ$ . GRG is a widely used gradient-based method for constrained nonlinear optimization problems with continuous decision variables. In this study, the objective was to maximize annual solar irradiation by optimizing the angles assigned to the adjustment periods. Starting from initial estimates, the algorithm iteratively updated these angles until convergence while satisfying the constraint in equation (11):

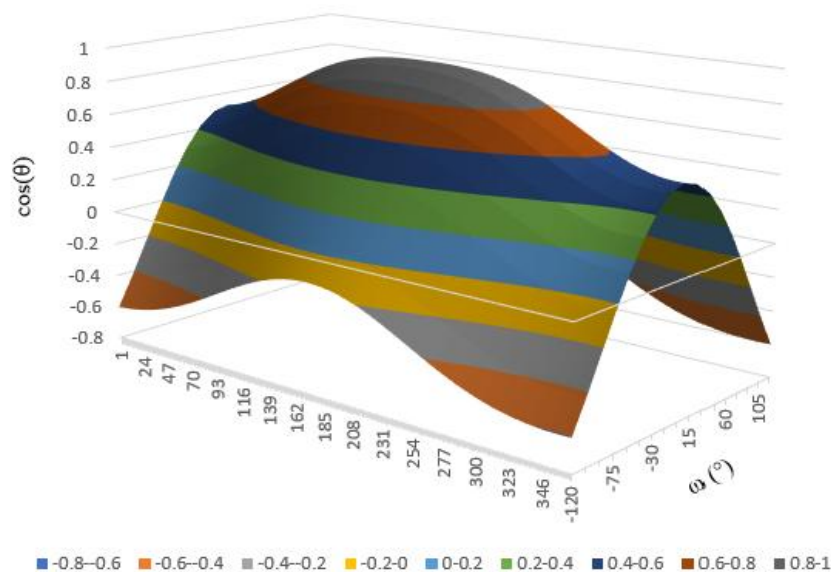
$$0^\circ \leq \beta_i \leq 90^\circ, i = 1, 2, \dots, m \quad (11)$$

The number of tilt-angle settings,  $m$ , depended on the selected strategy, and  $\beta_i$  represented the angle used during the  $i$ th adjustment period. For the seasonal and multiple-adjustment strategies, the set of angles was optimized to maximize annual irradiation subject to equation (11). These optimized combinations were then used to calculate annual irradiation for each strategy. Finally, irradiation gains were compared with the number of adjustments required to identify the most suitable strategy for Sulaymaniyah in terms of irradiation and implementation complexity.

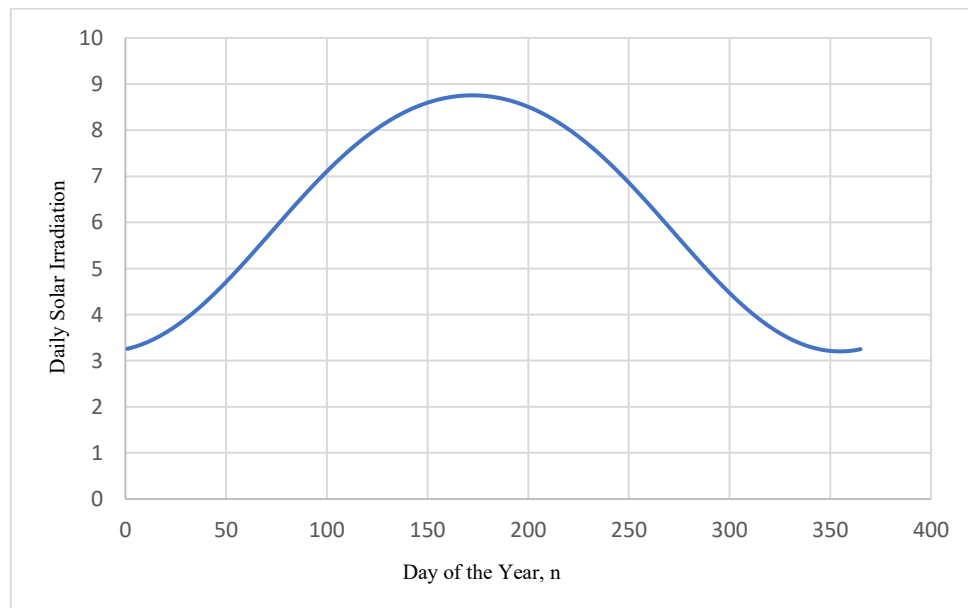
### 3. Results

#### 3.1. Annual Irradiation Analysis

The cosine of the incidence angle,  $\cos(\theta)$ , was analyzed as a function of day of the year ( $n$ ) and solar hour angle ( $\omega$ ) to evaluate the influence of panel tilt on incident irradiance under clear-sky conditions. Figure 3 shows the three-dimensional distribution of  $\cos(\theta)$  throughout the year for a horizontal panel ( $\beta = 0^\circ$ ) in Sulaymaniyah, excluding cloud and aerosol effects. The x-axis represents the day of the year ( $n = 1-365$ ), the y-axis represents the solar hour angle from  $-120^\circ$  to  $+120^\circ$ , and the z-axis represents  $\cos(\theta)$ , ranging from  $-0.8$  to  $1$  under the modeled conditions. Higher positive values of  $\cos(\theta)$  indicate closer alignment between the sun's rays and the panel normal, resulting in greater direct irradiance on the surface. Lower positive values indicate a larger angle of incidence and a smaller direct irradiance component. Peak irradiance occurs around day 181, near solar noon ( $\omega = 0^\circ$ ), reflecting the high solar elevation during summer and the resulting increase in direct radiation received by a horizontal surface. Figure 4 shows the corresponding daily irradiation for  $\beta = 0^\circ$ , with the highest values occurring during summer. The horizontal configuration was used as a baseline for comparison with the other configurations. Summing daily irradiation over 365 days yielded an annual total of  $2225 \text{ kWh/m}^2/\text{year}$ .



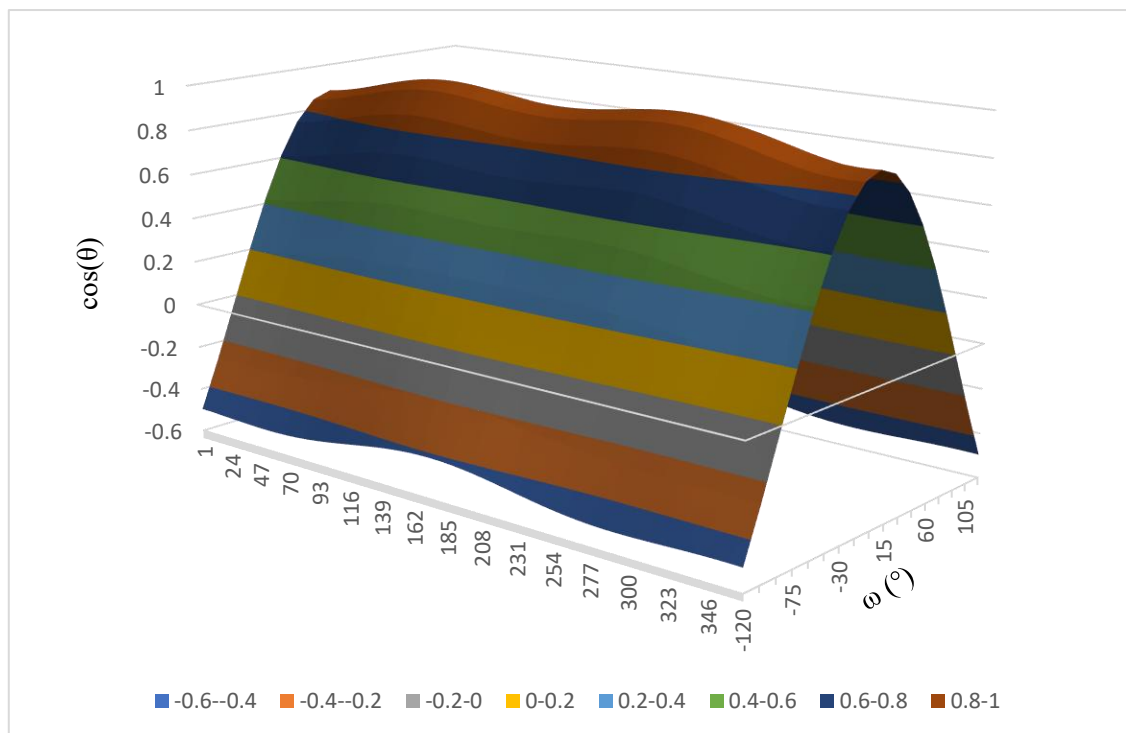
**Figure 3:** Three-dimensional distribution of the cosine of the incidence angle,  $\cos(\theta)$ , throughout the year for a horizontal photovoltaic panel ( $\beta = 0^\circ$ ).



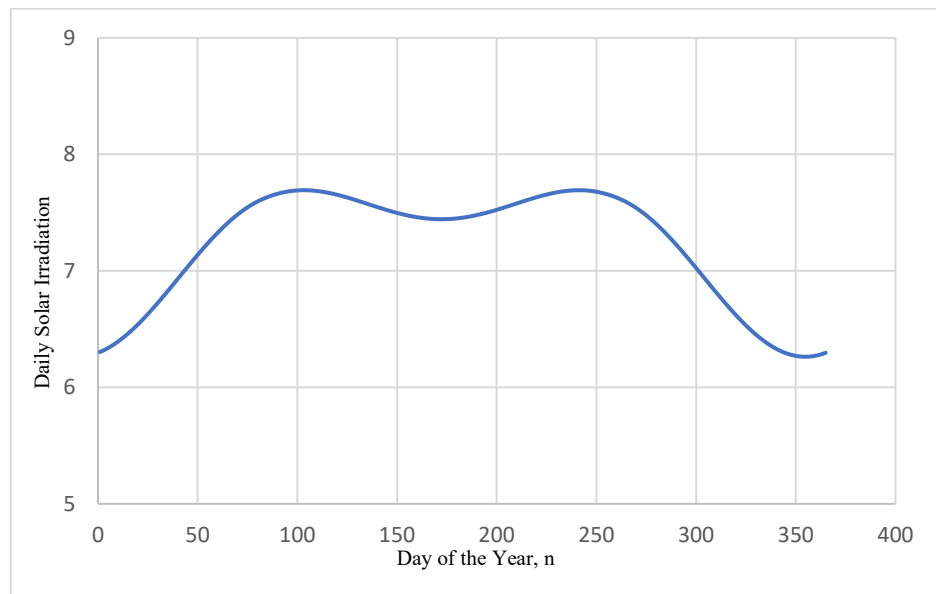
**Figure 4:** Daily solar irradiation throughout the year for a horizontal photovoltaic panel ( $\beta = 0^\circ$ ).

For the fixed tilt angle of  $30^\circ$ ,  $\cos(\theta)$  was calculated for all days of the year and solar hour angles between  $-120^\circ$  and  $+120^\circ$ , as shown in figure 5. The three-dimensional surface plot indicates a more uniform annual distribution than that of the horizontal configuration in figure 3. The distribution suggests improved alignment between the panel surface and incident solar rays over a larger part of the day and a wider range of solar hour angles. Consistent with this pattern, the calculated annual irradiation was higher at  $\beta = 30^\circ$  than at  $\beta = 0^\circ$ .

Annual irradiation at  $\beta = 30^\circ$  reached  $2638 \text{ kWh/m}^2/\text{year}$ , an increase of 18.5% relative to the horizontal configuration. The daily irradiation profile in figure 6 also shows a more uniform seasonal distribution. These results confirm that the conventional fixed tilt angle of  $30^\circ$  substantially improves annual irradiation capture relative to horizontal installation. Seasonal or more frequent adjustments can provide further gains.



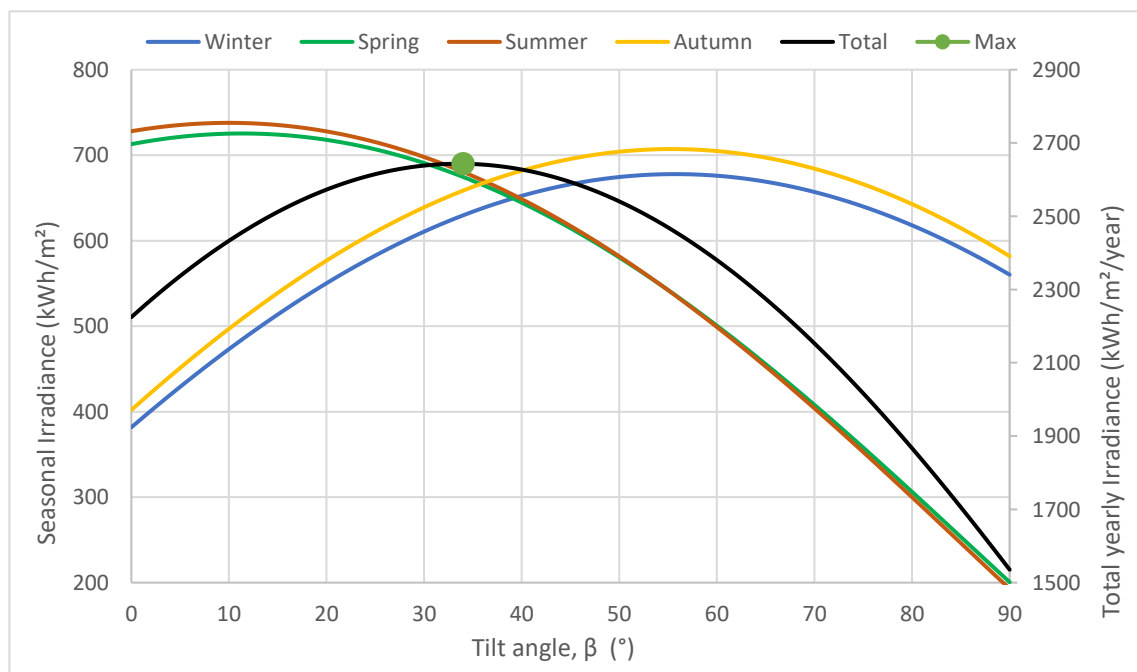
**Figure 5:** Three-dimensional distribution of  $\cos(\theta)$  throughout the year for a photovoltaic panel tilted at  $30^\circ$ .



**Figure 6:** Daily solar irradiation throughout the year for a photovoltaic panel tilted at 30°.

### 3.2. Annual and Seasonal Tilt-angle Analysis

Figure 7 shows the variation in seasonal and annual irradiation with panel tilt angle ( $\beta$ ). The x-axis represents tilt angles from 0° to 90°, the left y-axis represents seasonal irradiation, and the right y-axis represents annual irradiation. The seasons were defined as follows: winter, days 356–365 and 1–79; spring, days 80–170; summer, days 171–262; and autumn, days 263–355 [1]. The green and red curves indicate that lower tilt angles, approximately 10°–20°, produce higher irradiation during spring and summer. Conversely, the purple and blue curves show that larger angles, approximately 50°–70°, are more favorable during autumn and winter. This pattern reflects the influence of seasonal changes in solar elevation on optimal panel tilt. The annual irradiation curve, shown in black, was obtained by summing the four seasonal totals at each tilt angle. It reached a maximum of 2643.2 kWh/m<sup>2</sup>/year at approximately  $\beta = 34^\circ$ . Thus, 34° was the optimal fixed tilt angle for Sulaymaniyah under the modeled clear-sky conditions, providing the highest annual irradiation among the fixed configurations evaluated.



**Figure 7:** Seasonal and annual solar irradiation as a function of panel tilt angle.

### 3.3. Biannual and Multiple-angle Adjustments

The influence of adjusting panel tilt throughout the year was investigated to identify further improvements in annual irradiation capture. Figure 8 presents daily irradiation as a function of day of the year and panel tilt angle ( $\beta$ ). The surface shows clear seasonal variation. At low tilt angles, daily irradiation reaches approximately 8–10 kWh/m<sup>2</sup>/day during summer but is lower during winter. The figure also shows seasonal changes in the optimal tilt angle. Lower angles maximize irradiation during summer, whereas larger angles are more favorable during winter. This relationship between solar position and incident irradiation supports the use of seasonal adjustments and demonstrates the importance of selecting tilt angles according to the time of year.

Figure 9 presents a two-dimensional color map of irradiation as a function of day of the year and panel tilt angle. Dark blue areas at the top represent the lowest irradiation, while lighter blue areas indicate higher values of approximately 8–10 kWh/m<sup>2</sup>/day. The yellow region spans the widest range and represents conditions favorable for solar radiation capture. The map shows that the highest summer irradiation occurs at low tilt angles, approximately 5°–25°, whereas larger angles, typically 55°–65°, are more favorable during winter. These seasonal optimal regions were used to define the tilt-angle adjustment strategies ( $\beta_1$ – $\beta_{66}$ ), which are overlaid on the irradiation map in figure 10 and compared in section 3.4.

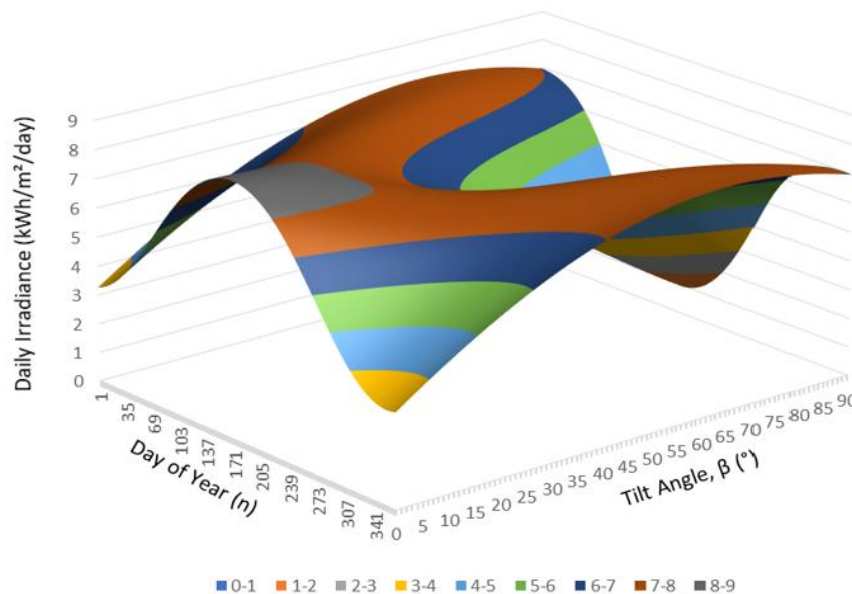


Figure 8: Three-dimensional distribution of daily solar irradiation as a function of day of the year and panel tilt angle.

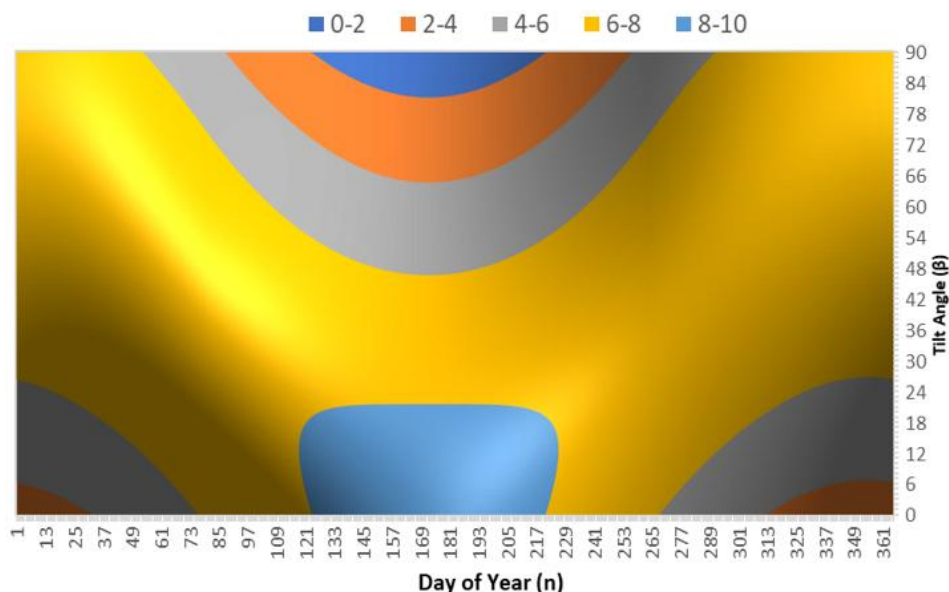
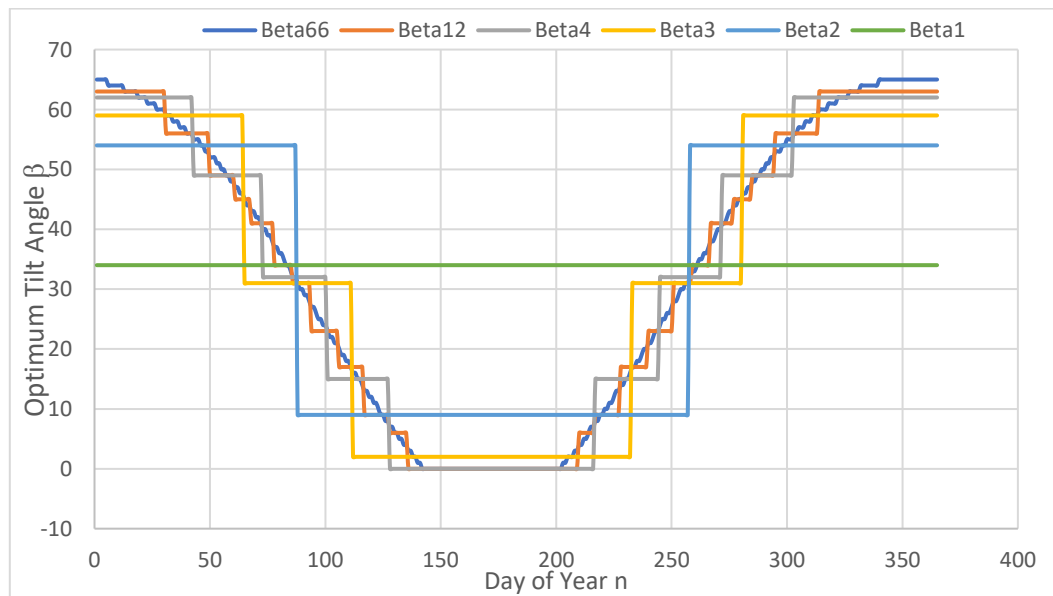


Figure 9: Color-coded solar irradiation contours as a function of day of the year and panel tilt angle.



**Figure 10:** Tilt-angle adjustment strategies ( $\beta_1$ – $\beta_{66}$ ) overlaid on the solar irradiation map.

### 3.4. Comparison of Tilt-angle Strategies

The seasonal optimal tilt-angle ranges were used to evaluate the proposed adjustment strategies. Figure 10 shows six strategies overlaid on the irradiation map:  $\beta_1$ , an annual fixed tilt;  $\beta_2$ , biannual adjustment;  $\beta_3$  and  $\beta_4$ , three and four adjustments per year;  $\beta_{12}$ , monthly adjustment; and  $\beta_{66}$ , sixty-six adjustments per year. For  $\beta_1$ , the optimal annual tilt angle of  $34^\circ$  remained fixed throughout the year. The  $\beta_2$  strategy used approximately  $10^\circ$  in summer and  $55^\circ$  in winter. These angles were selected from the optimal summer and winter irradiation regions in figure 9. More frequent strategies, particularly  $\beta_{12}$  and  $\beta_{66}$ , followed the optimal irradiation trajectory more closely and produced slightly higher annual totals. However, these gains were modest relative to the additional adjustments required.

Table 1 summarizes annual irradiation for all evaluated strategies and the gains relative to horizontal installation ( $\beta = 0^\circ$ ) and the conventional fixed tilt angle ( $\beta = 30^\circ$ ). The highest annual irradiation, approximately  $2898 \text{ kWh/m}^2/\text{year}$ , was obtained using  $\beta_{66}$ . Its advantage over monthly adjustment was minimal, and its gain over biannual adjustment remained limited despite the much larger number of adjustments. The  $\beta_2$  configuration, using approximately  $10^\circ$  in summer and  $55^\circ$  in winter, achieved approximately  $2850 \text{ kWh/m}^2/\text{year}$  with only two adjustments annually. Strategies  $\beta_3$ ,  $\beta_4$ ,  $\beta_{12}$ , and  $\beta_{66}$  provided additional gains of only approximately 1–2%. These small increases are unlikely to offset the additional operational complexity and maintenance associated with more frequent adjustments. Biannual adjustment therefore offers the most practical balance between annual irradiation and implementation simplicity for the PV installations considered in Sulaymaniyah.

**Table 1:** Annual solar irradiation and gains achieved using different tilt-angle adjustment strategies.

| Strategy                     | Adjustments per year | Annual irradiation ( $\text{kWh/m}^2/\text{year}$ ) | Gain vs. $\beta = 0^\circ$ | Gain vs. $\beta = 30^\circ$ |
|------------------------------|----------------------|-----------------------------------------------------|----------------------------|-----------------------------|
| Fixed ( $\beta = 34^\circ$ ) | 1                    | 2643.2                                              | 18.80%                     | 0.20%                       |
| Biannual                     | 2                    | 2850                                                | 28.10%                     | 8.00%                       |
| Three times annually         | 3                    | 2878.9                                              | 29.40%                     | 9.10%                       |
| Quarterly                    | 4                    | 2892.4                                              | 30.00%                     | 9.60%                       |
| Monthly                      | 12                   | 2897                                                | 30.20%                     | 9.80%                       |
| $\beta_{66}$                 | 66                   | 2898.2                                              | 30.30%                     | 9.90%                       |

## 4. Discussion

The annual fixed-tilt results were compared with the PVGIS-SARAH3 database [32] as an external benchmark for Sulaymaniyah ( $35.57^\circ \text{ N}$ ,  $45.43^\circ \text{ E}$ ). PVGIS identified an optimal south-facing fixed tilt angle of  $31^\circ$ , with annual in-plane irradiation of  $2086.06 \text{ kWh/m}^2$ , compared with the optimal angle of  $34^\circ$  obtained in this study. The  $3^\circ$  difference indicates close agreement between the optimal angles

despite differences in irradiance modeling assumptions. The higher annual irradiation predicted here, 2643.2 kWh/m<sup>2</sup>, reflects the model's idealized assumptions, whereas PVGIS-SARAH3 incorporates long-term satellite-derived climatic conditions.

Based on the simulation results, biannual tilt-angle adjustment is recommended for PV installations in Sulaymaniyah. Angles of approximately 10° in summer and 55° in winter produced annual irradiation of approximately 2850 kWh/m<sup>2</sup>/year, about 8% higher than that obtained with the conventional fixed tilt angle of 30°, while requiring only two adjustments annually. This balance between irradiation gain and implementation effort makes biannual adjustment particularly suitable for residential, commercial, and small-scale PV systems in Sulaymaniyah and locations with similar clear-sky conditions.

The optimal fixed tilt angle identified here is broadly consistent with values reported in previous Iraqi studies. Ibrahim and Aljanabi [26] analyzed all 18 governorates and reported an optimal angle of approximately 38.3° for Iraq. The 34° value obtained for Sulaymaniyah is slightly lower but falls within the range reported for Iraqi locations. Kadhim *et al.* [6] reported optimal angles of 35°, 33°, and 31° for Kirkuk, Baghdad, and Nasiriyah, respectively, from north to south. Sulaymaniyah's latitude of 35.57° N is close to Kirkuk's latitude of 35.47° N, and their similar optimal angles—34° and 35°, respectively—are consistent with the principle that optimal fixed tilt angles increase with latitude.

Other studies, including those by Taha and Hameed [13] for Duhok and Al-Shammari *et al.* [16] for Baghdad, determined optimal angles for specific annual or monthly periods but did not quantify the marginal gains from increasing adjustment frequency. In a study covering all 18 Iraqi provinces, Zurfi *et al.* [12] reported that monthly optimal tilts increased energy yield by 5–6% relative to an annual fixed tilt. The present study found that increasing adjustment frequency beyond the biannual 10°/55° strategy improved annual irradiation by only approximately 1–2% in Sulaymaniyah. Differences in scope and modeling assumptions explain these apparently different findings. Zurfi *et al.* [12] compared a single annual fixed angle with fully optimized monthly angles, whereas the present comparison evaluated the incremental benefit of more frequent adjustments over a two-angle biannual strategy. The results therefore address different comparisons, while the fixed-angle findings remain broadly consistent with those of independent Iraqi studies.

The main strength of this study is its systematic comparison of six tilt-angle strategies for Sulaymaniyah, from one fixed angle to sixty-six adjustments per year, within a single modeling framework. This comparison quantifies the irradiation gain associated with each increase in adjustment frequency, and the resulting optimal fixed angle is broadly consistent with PVGIS-SARAH3 and previous Iraqi studies. The main limitation is that the model assumed clear-sky conditions and considered only direct-beam radiation, excluding diffuse and ground-reflected radiation, clouds, and aerosols; therefore, the annual irradiation values are higher than those obtained from PVGIS.

## 5. Conclusions

Solar geometry modeling was used to determine optimal PV panel tilt angles under clear-sky conditions in Sulaymaniyah, Iraq. The results confirmed that tilt-angle optimization increased annual irradiation received by the panels relative to the reference fixed-tilt configurations. A fixed angle of approximately 34° provided the highest annual irradiation among the year-round configurations evaluated. Biannual adjustment, using 10° in summer and 55° in winter, offered an effective balance between irradiation gains and practical implementation. Although quarterly, monthly, and β<sub>66</sub> strategies produced slightly higher annual irradiation, their additional gains over biannual adjustment were limited to approximately 1–2%. These gains may not justify the additional operational effort and maintenance requirements. Biannual adjustment therefore represents the most practical and cost-effective option considered for residential and commercial PV installations in Sulaymaniyah. Across the evaluated strategies, tilt-angle optimization increased annual irradiation by more than 30% relative to horizontal installation and by approximately 10% relative to the conventional fixed tilt angle of 30°. These findings provide practical guidance for PV system design, installation, and optimization in Sulaymaniyah and regions with similar climatic characteristics.

This study considered only clear-sky simulation conditions and excluded diffuse radiation, ground-reflected radiation, and variable atmospheric effects. Future studies should incorporate these

components and validate the model against measured solar irradiance and PV electricity generation data from Sulaymaniyah. An economic analysis should also evaluate the costs and benefits of the different adjustment strategies.

**Author contributions:** **Shivan S. Mahmood:** Conceptualization, Investigation, Methodology, Formal Analysis, Software, Validation, Visualization, Writing-Original Draft. **Alaa M. Abdulrahman:** Supervision, Writing – Review & Editing. **Ghamgeen I. Rashed:** Supervision, Writing – Review & Editing.

**Data availability:** Data will be available upon reasonable request by authors.

**Conflicts of interest:** The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

**Funding:** The authors did not receive support from any organization for the conducting of the study.

## References

- [1] J. A. Duffie and W. A. Beckman, *Solar Engineering of Thermal Processes*, 4th ed. Hoboken, NJ, USA: Wiley, 2013, doi: 10.1002/9781118671603.
- [2] H. Mousazadeh, A. Keyhani, H. Mobli, A. Javadi, A. Sharifi, and K. Abrinia, "A review of principle and sun-tracking methods for maximizing solar systems output," *Renewable and Sustainable Energy Reviews*, vol. 13, no. 8, pp. 1800–1818, Oct. 2009, doi: 10.1016/j.rser.2009.01.022.
- [3] S. Rehman and I. M. El-Amin, "Study of a solar PV–diesel–battery hybrid power system for a remotely located population near Rafha, Saudi Arabia," *Energy*, vol. 35, no. 12, pp. 4986–4995, 2010, doi: 10.1016/j.energy.2010.08.025.
- [4] International Renewable Energy Agency, *Renewable Power: Sharply Falling Generation Costs in 2017*. Abu Dhabi, UAE: IRENA, 2017.
- [5] W. A. M. Al-Shohani, A. J. Khaleel, H. J. Dakkama, and A. Q. Ahmed, "Optimum tilt angle of the photovoltaic modules in Baghdad, Iraq," *Applied Solar Energy*, vol. 58, no. 4, pp. 517–525, 2022, doi: 10.3103/S0003701X22040028.
- [6] S. A. Kadhim, M. K. S. Al-Ghezi, and W. Y. Shehab, "Optimum orientation of non-tracking solar applications in Baghdad City," *International Journal of Heat and Technology*, vol. 41, no. 1, pp. 125–134, 2023, doi: 10.18280/ijht.410113.
- [7] A. A. K. Al-Waeli, K. A. Al-Asadi, and M. M. Fazleena, "The impact of Iraq climate condition on the use of solar energy applications in Iraq: A review," *International Journal of Science and Engineering Investigations*, vol. 6, pp. 64–73, 2017.
- [8] A. George and R. Anto, "Analytical and experimental analysis of optimal tilt angle of solar photovoltaic systems," *International Conference on Green Technologies*, Coimbatore, India, Dec. 2012, pp. 234–239, doi: 10.1109/ICGT.2012.6477978.
- [9] M. Benghanem, "Optimization of tilt angle for solar panel: Case study for Madinah, Saudi Arabia," *Applied Energy*, vol. 88, no. 4, pp. 1427–1433, Apr. 2011, doi: 10.1016/j.apenergy.2010.10.001.
- [10] K. Skeiker, "Optimum tilt angle for solar collectors used in Syria," *Energy Conversion and Management*, vol. 50, no. 9, pp. 2439–2443, Sep. 2009, doi: 10.1016/j.enconman.2009.05.031.
- [11] I. Daut, M. Irwanto, Y. M. Irwan, N. Gomes, and N. S. Ahmad, "Clear sky global solar irradiance on tilt angles of photovoltaic module in Perlis, Northern Malaysia," in *2011 International Conference on Electrical, Control and Computer Engineering (InECCE)*, Kuantan, Malaysia, 2011, pp. 445–450, doi: 10.1109/INECCE.2011.5953923.
- [12] A. Zurfi, A. A. R. Altaf, and A. Ibrahim, "Investigation of optimal tilt, orientation, and tracking of a solar PV system in Iraq," *International Journal of Power Electronics and Drive Systems*, vol. 16, no. 3, pp. 1914–1925, 2025, doi: 10.11591/ijpeds.v16.i3.pp1914-1925.
- [13] H. M. Taha and S. M. Hameed, "Optimization of tilt angle of a PV system to get maximum generated power: A case study," *Kurdistan Journal of Applied Research*, vol. 5, no. 2, pp. 71–81, 2020, doi: 10.24017/science.2020.2.7.
- [14] F. A. Ali, "Optimum tilt angle of photovoltaic panels for some Iraq cities," *Journal of University of Babylon for Engineering Sciences*, vol. 26, no. 1, pp. 155–163, 2018. [Online]. Available: <https://www.journalofbabylon.com/index.php/IUBES/article/view/1191>.
- [15] M. Guo, Z. Zang, N. Gao, T. Liang, and T. Zhu, "Optimal tilt angle and orientation of photovoltaic modules using harmony search algorithm in different climates of China," *Applied Sciences*, vol. 7, no. 10, Art. no. 1028, 2017, doi: 10.3390/app7101028.
- [16] S. A. Al-Shammari, A. A. Karamallah, and S. Aljabair, "Optimization of tilt angle and experimental study of standalone PV system for clean energy home supply in Baghdad," *FME Transactions*, vol. 49, no. 3, pp. 664–672, 2021, doi: 10.5937/fme2103664A.
- [17] I. Shariah, M. A. Al-Akhras, and I. A. Al-Omari, "Optimizing the tilt angle of solar collectors," *Renewable Energy*, vol. 26, no. 4, pp. 587–598, 2002, doi: 10.1016/S0960-1481(01)00106-9.
- [18] T. O. Kaddoura, M. A. M. Ramli, and Y. A. Al-Turki, "On the estimation of the optimum tilt angle of PV panel in Saudi Arabia," *Renewable and Sustainable Energy Reviews*, vol. 65, pp. 626–634, 2016, doi: 10.1016/j.rser.2016.07.032.
- [19] A. A. Ashetehe, B. B. Gessesse, and F. Shewarega, "Development of optimal tilt angle models of a photovoltaic module for maximum power production: Ethiopia," *International Journal of Photoenergy*, vol. 2022, Art. no. 8729570, 2022, doi: 10.1155/2022/8729570.
- [20] R. Melhem and Y. Shaker, "Optimum tilt angle and solar radiation of photovoltaic modules for Gulf Collaboration Council countries," *International Journal of Energy Research*, vol. 2023, Art. no. 8381696, 2023, doi: 10.1155/2023/8381696.

- [21] M. Tamoor, A. R. Bhatti, M. Farhan, A. Rasool, and A. Sherefa, "Optimizing tilt angle of PV modules for different locations using isotropic and anisotropic models to maximize power output," *Scientific Reports*, vol. 14, Art. no. 30197, 2024, doi: 10.1038/s41598-024-81826-9.
- [22] Y. Liu *et al.*, "Spatial estimation of the optimum PV tilt angles in China by incorporating ground with satellite data," *Renewable Energy*, vol. 189, pp. 1249–1258, 2022, doi: 10.1016/j.renene.2022.03.072.
- [23] A. K. Abdelaal and A. El-Fergany, "Estimation of optimal tilt angles for photovoltaic panels in Egypt with experimental verifications," *Scientific Reports*, vol. 13, Art. no. 3268, 2023, doi: 10.1038/s41598-023-30375-8.
- [24] N. Lu and J. Qin, "Optimization of tilt angle for PV in China with long-term hourly surface solar radiation," *Renewable Energy*, vol. 229, Art. no. 120741, 2024, doi: 10.1016/j.renene.2024.120741.
- [25] A. A. Teyabeen and F. Mohamed, "Estimation of the optimum tilt angle of solar PV panels to maximize incident solar radiation in Libya," *Energies*, vol. 17, no. 23, Art. no. 5891, 2024, doi: 10.3390/en17235891.
- [26] Z. Ibrahim and M. Aljanabi, "Influence of tilt angle on PV output for solar energy optimization in Iraq," *Salud, Ciencia y Tecnología – Serie de Conferencias*, vol. 3, Art. no. 871, 2024, doi: 10.56294/sctconf2024871.
- [27] H. U. Manzoor, S. M. Aaqib, T. Manzoor, F. Azeem, M. W. Ashraf, and S. Manzoor, "Effect of optimized tilt angle of PV modules on solar irradiance for residential and commercial buildings in different cities of Pakistan: Simulation-based study," *Energy Science & Engineering*, vol. 13, no. 4, pp. 1831–1845, 2025, doi: 10.1002/ese3.70004.
- [28] E. Coffari, "The sun and the celestial vault," in *Solar Energy Engineering*, A. A. M. Sayigh, Ed. New York, NY, USA: Academic Press, 1977, pp. 5–36.
- [29] R. A. Messenger and A. Abtahi, *Photovoltaic Systems Engineering*, 4th ed. Boca Raton, FL, USA: CRC Press, 2017.
- [30] H. Muslim, "Solar tilt angle optimization of PV systems for different case studies," *EAI Endorsed Transactions on Energy Web*, vol. 6, pp. 1–8, 2019, doi: 10.4108/eai.13-7-2018.157038.
- [31] A. K. S. Al-Sayyab and M. K. Taher, "Optimum tilted angle of photovoltaic cell located in northern Iraq cities to get maximum generated electric power," in *Proc. National Renewable Energies Conference and Their Applications*, 2013. Accessed: Aug. 30, 2026. [Online]. Available: <https://www.researchgate.net/publication/313726087>.
- [32] European Commission, Joint Research Centre, "Photovoltaic Geographical Information System (PVGIS), version 5.3," PVGIS-SARAH3 solar radiation database. Accessed: Aug. 16, 2026. [Online]. Available: [https://re.jrc.ec.europa.eu/pvg\\_tools/en/tools.html](https://re.jrc.ec.europa.eu/pvg_tools/en/tools.html).