Salud, Ciencia y Tecnología - Serie de Conferencias. 2024; 3:871
doi: 10.56294/sctconf2024871

Category: STEM (Science, Technology, Engineering and Mathematics)

ORIGINAL

Influence of Tilt Angle on PV Output for Solar Energy Optimization in Iraq

Influencia del ángulo de inclinación en la producción fotovoltaica para la optimización de la energía solar en Iraq

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Cite as: Ibrahim Z, Aljanabi M. Influence of tilt angle on PV output for solar energy optimization in Iraq . Salud, Ciencia y Tecnología - Serie de Conferencias. 2024; 3:871. https://doi.org/10.56294/sctconf2024871

Submitted: 06-02-2024 **Revised:** 14-04-2024 **Accepted:** 10-06-2024 **Published:** 11-06-2024

Editor: Dr. William Castillo-González

Note: paper presented at the 3rd Annual International Conference on Information & Sciences (AICIS'23).

ABSTRACT

It has been established through investigation that the optimal inclination of photovoltaic (PV) modules is a critical factor for harnessing the maximal quantity of solar radiation impinging upon solar arrays. The specificity of the requisite angle for each site is underscored, contingent upon the solar trajectory over daily, monthly, and annual cycles. The determination of this optimal angle is imperative for maximizing the yield from solar PV systems within the confines of Iraq. Worldwide locales have seen the application of varied methodologies for ascertaining the correct tilt angle. The efficacy of PV systems is observed to be significantly influenced by whether a fixed or a tracking system is employed to modulate the tilt angle. The present manuscript delineates the contemporary state of research and praxis pertaining to the influence of tilt angle on PV output, employing an array of optimization techniques. Furthermore, the work offers a disquisition on the determination of the most advantageous tilt angle to optimize energy acquisition in Iraq. The inquiry reveals that an optimal tilt angle for Iraq is discerned to be 38,3. This compendium is intended to augment the compendium of knowledge available to designers and scholars endeavoring to pinpoint the most favorable tilt angle for solar PV systems in any given Iraqi locale.

Keywords: Tilt Angle; PV Module; Tilt Irradiation; Optimum Tilt; Surface Orientation; Solar Energy.

RESUMEN

La investigación ha demostrado que la inclinación óptima de los módulos fotovoltaicos (FV) es un factor crítico para aprovechar la máxima cantidad de radiación solar que incide sobre los paneles solares. La especificidad del ángulo necesario para cada emplazamiento depende de la trayectoria solar a lo largo de los ciclos diarios, mensuales y anuales. La determinación de este ángulo óptimo es imprescindible para maximizar el rendimiento de los sistemas solares fotovoltaicos dentro de los confines de Irak. En todo el mundo se han aplicado diversas metodologías para determinar el ángulo de inclinación correcto. Se ha observado que la eficacia de los sistemas fotovoltaicos depende en gran medida de si se emplea un sistema fijo o de seguimiento para modular el ángulo de inclinación. El presente manuscrito describe el estado actual de la investigación y la práctica en relación con la influencia del ángulo de inclinación en la producción fotovoltaica, empleando una serie de técnicas de optimización. Además, el trabajo ofrece una disquisición sobre la determinación del ángulo de inclinación más ventajoso para optimizar la obtención de energía en Irak. La investigación revela que el ángulo de inclinación óptimo para Irak es de 38,3. El objetivo de este compendio es aumentar los conocimientos de que disponen los diseñadores y estudiosos que tratan de determinar el ángulo de inclinación más favorable para los sistemas solares fotovoltaicos en cualquier localidad iraquí.

Palabras clave: Ángulo de Inclinación; Módulo FV; Irradiación de Inclinación; Inclinación Óptima; Orientación de la Superficie; Energía Solar.

INTRODUCTION

In the realm of renewable resources, solar energy is esteemed as a paramount, perpetual, and cleaner alternative. Photovoltaic (PV) power generators, lauded for their efficacy, transfer solar irradiation directly into electric power, with the absence of requisite moving parts being a salient feature.[1,2] Solar PV systems stand at the forefront of effective solar energy utilization methods.[3] Optimal output from a PV panel is achieved when it is subjected to rays that impinge perpendicularly upon its surface.[4] The energy harvested is contingent upon a myriad of factors including local solar irradiation, the reflective attributes of the ground, and crucially, the orientation and tilt of the PV array. It is the tilt angle, in particular, which dictates the magnitude of irradiation received by the PV array's plane. The efficiency of solar panels is profoundly impacted by their orientation and tilt angle.[5] Thus, for maximum solar energy capture in a given locale, precise calibration of the solar arrays tilt and orientation is imperative. While active sun trackers, mechanical or electromechanical, represent an ideal solution for optimizing these parameters, they present challenges in terms of initial outlay and operational energy consumption.[6] Consequently, periodic manual adjustments of the PV module's tilt may present a more viable alternative. The choice of tilt and orientation significantly affects the solar energy yield, with the most favorable orientation typically being southward in the northern hemisphere, and the optimal tilt being latitude-dependent.[4]

Multiple studies have been devoted to the optimization of tilt angles for PV modules across various latitudes.[7,8] For instance, adjustments to the tilt angle have been shown to enhance PV performance significantly.[9] Moreover, monthly adjustments have been found to yield nearly the highest possible solar irradiation, comparable to daily adjustments, with a notable annual increase.[10] Recommendations for optimal tilt angles vary, with some suggesting alignment with the local latitude,[11] while others propose latitude plus or minus a fixed angle, depending on the region and application.[12,13] In Iraq, the investigation into the optimal tilt angles is less prolific but critical due to the variation in geographic coordinates affecting solar irradiation.[14] Astronomical factors, including the Earth's shape and axial tilt, necessitate the use of tracking mechanisms for PV modules to effectively follow the sun's trajectory.[15] Variations in solar irradiation at Earth's surface are influenced by atmospheric clarity, shading, latitude, and other environmental factors.[16] Consequently, solar energy accumulation is a temporal and spatial variable, with the optimal tilt angle for maximum solar irradiation being location-specific.[17]

Solar energy, a vital renewable resource sustaining terrestrial life, is utilized by Earth's flora for converting it into essential chemical energy. In the previous century, its application as a life necessity has emerged, notably through photovoltaic (PV) modules, which transmute solar into electrical energy. Despite global advancements, augmenting electrical efficiency and curbing production costs remain central aims among researchers.

The power yield from PV modules is influenced by various factors, including solar irradiance intensity, ambient temperature, wind speed, module positioning and ventilation, alongside environmental elements like dust, pollution, and shading.[18] The total solar energy output from PV modules, under given solar cell efficiency and meteorological conditions, is contingent on optimal module positioning. This positioning is gauged in relation to azimuth (vertical plane) and inclination angles (horizontal plane). PV cell efficiency, benchmarked by Standard Test Conditions (STC), fluctuates based on operating temperature and cell type (monocrystalline silicon around 23 %, polycrystalline silicon 16,0 % - 18 %, and thin amorphous silicon roughly 9,5 %.[19] Elevated temperatures increase current in PVs but reduce voltage and electrical power.[20]

Numerous studies have concentrated on maximizing accumulated energy through 'optimal module positioning' across diverse global locales. These optimal positions vary over periods (hourly, daily, monthly, seasonal, semi-annual, and annual) and depend on geographical and environmental conditions. Research examples include Hafez et al.[21] optimal tilt angle determination in Brunei Darussalam using solar collectors and simulation; El et al.[22] findings on efficient PV module operation during low solar irradiance periods; Boji´c et al.[23] calculation of optimal tilt and azimuth angles in four French cities; Kacira et al.[24] evaluation of monthly optimal tilt angles in Sanliurfa, Turkey; and Lubitz[25] determination of optimal tilt angles across various U.S. sites through simulated studies.

Further investigations, such as Wada et al.[26] in Gobo City, Japan, and Talebizadeha et al.[27] in Iran using genetic algorithms, have delved into optimal tilt and azimuth angles for different periods. Studies like Chang[28] in Taiwan, utilizing hybrid algorithms, and Hussein et al.[29] in Cairo, Egypt, using TRNSYS software, have also contributed significant insights. Such diverse methodologies highlight the complexity and site-specific nature of optimizing PV module positioning.

This comprehensive literature review underscores that while various methodologies and objectives have been employed to determine PV optimum tilt and positioning across multiple sites, no such analysis exists for Iraq, signaling a gap that warrants investigation. This study introduces the potential and optimal tilt angles for maximizing solar irradiance in Iraq, relevant to solar energy applications like PV modules and collectors, across its 18 governorates. Utilizing hourly solar irradiance data, provided by NSRDB: National Solar Radiation Database, this work showcases the potential of solar energy in Iraq for future solar power/thermal plant construction. Iraq's 18 governorates are detailed in table 1, with table 2 presenting the average solar declination monthly and daily for each governorate.

Table 1. Iraqi's governorates coordinates

Governorate	Latitude (N)	Longitude (E)	Elevation (m)
Anbar	32,55	41,91	45
Babylon	32,29	44,26	34
Baghdad	33,31	44,36	34
Basra	30,52	47,77	5
Dhi Qar	31,1	46,36	5
Diyala	33,53	44,64	50
Duhok	36,86	42,98	565
Erbil	36,19	43,99	390
Karbala	32,6	44,01	28
Kirkuk	35,46	44,39	303
Maysan	31,83	47,14	12
Muthanna	31,33	45,29	15
Najaf	32,01	44,32	61
Nineveh	36,34	43,15	223
Qadisiyyah	31,97	44,89	61
Saladin	34,59	43,67	137
Sulaymaniyah	35,55	45,43	882
Wasit	32,51	45,81	35

Table 2. Recommended day average and declination for each month

Month	Day of year	Declination (δ o)
January	17	20,92
February	47	13,29
March	75	2,42
April	105	9,14
May	135	18,76
June	162	23,09
July	198	21,18
August	228	13,45
September	258	2,22
October	288	9,6
November	318	18,91
December	344	23,05

This article aims to assess the optimal tilt angle for enhanced radiation reception on PV panels in Iraq, providing a synthesis of current research and methodologies for the analysis and optimization of PV panel

https://doi.org/10.56294/sctconf2024871

tilt angles. The objective is to delineate the optimal tilt angles for PV modules in Iraq to maximize energy collection, thereby aiding in the efficient harnessing of solar energy across different Iraqi sites.

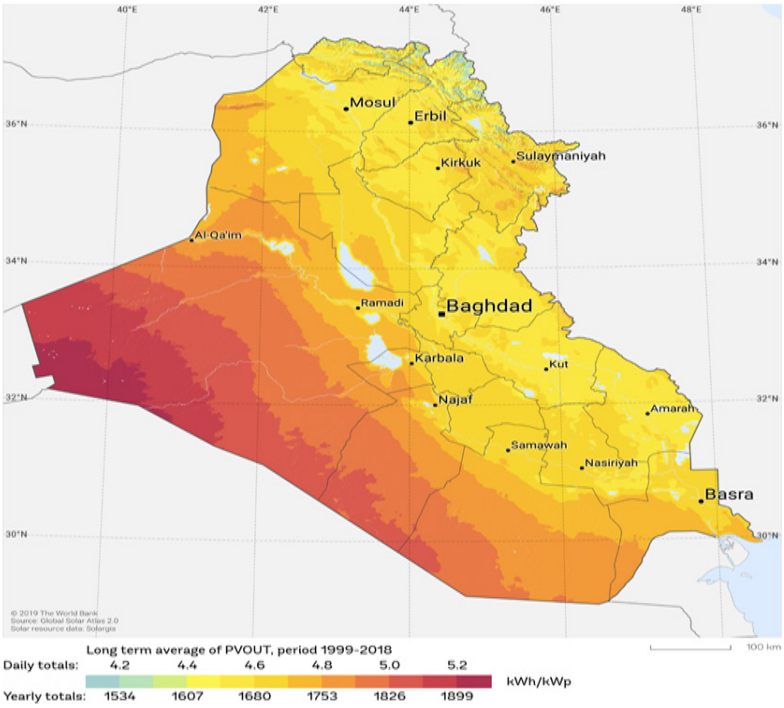

Figure 1. Solar resource and PV power potential map

METHOD

In the investigative effort presented, a compendium of research delineating the optimal tilt angle and its correlation with latitude is examined, with the aim of distilling a lucid understanding of this pivotal parameter. Initial scrutiny is directed towards endeavors that mathematically articulate the optimal tilt angle; through this inquiry, the formulas governing the optimal tilt angle for Iraq are affirmed, we need more information about optimization techniques used in PV system with different tilt angles. Subsequently, studies probing the tilt angle-latitude nexus are considered, culminating in the ascertainment of the most advantageous tilt angle at specified Iraqi latitudes.

Optimum Tilt Angle Determination

The angle between the solar plane of a photovoltaic (PV) module and the horizontal plane is identified as the tilt angle.[30] It assumes a positive value when the module plane inclines towards the equator and a negative value when it tilts poleward. The reflective component of solar irradiation, often complex to quantify and typically not a significant factor in solar energy assessments, is generally disregarded for simplification. This assumption yields a standard approximation of solar insolation on the PV module. The aggregate solar irradiation received by a tilted surface () encompasses the direct or beam solar irradiation and the diffuse irradiation () incident on the tilted plane of the PV module, as expressed by equation 1.

$$H_T = \left(H_g - H_d\right)R_b + H_g\rho\frac{1-coscos\,\beta}{2} + H_dR_d \qquad (1)$$

The computation of the total solar irradiation on a tilted surface involves varying the tilt angle between 0° and 90°. For grassland surfaces, the albedo (ρ) is assumed to be 0,3. The tilt angle is considered optimal when the solar irradiation on the tilted surface () reaches its zenith.[31] Given known values of and the ratio, the monthly average daily irradiation on a tilted surface can be calculated. The optimum tilt angle for a fixed orientation is deduced by resolving equation 2 for the tilt angle.

$$\frac{d}{d\beta}\left(\underline{H_T}\right) = 0 \qquad (2)$$

$$\frac{d}{d\beta}\left(\underline{R_b}\right) = 0 \qquad (3)$$

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$$\Rightarrow \sin\sin(\varphi-\beta)\ \cos\cos\delta\ \sin\sin\omega_s - \frac{\pi}{180}\omega_s\cos\cos(\varphi-\beta)\ \sin\sin\frac{\delta}{\cos}\cos\varphi\ \cos\cos\delta\ \sin\sin\omega_s + \frac{\pi}{180}\omega_s\sin\sin\varphi\ \sin\sin\delta \quad (4)$$

$$\Rightarrow \beta = \varphi - \left(\frac{\frac{\pi}{180}\omega_s sinsinsin\,\delta}{coscoscos\,\delta\ coscoscos\,\omega_s}\right) \quad (5)$$

At a specific locale and month, fixed values of latitude (φ), sunset hour angle (ωs), and solar declination (δ) allow for the straightforward determination of the solar PV module's optimal tilt angle.[32]

The preliminary step involves ascertaining the average daily global, diffuse, and direct solar energy for the chosen Iraqi locations using historical data. The precise calculation of the optimum tilt angle for a solar PV module is critical for its effective operation, as improper orientation can result in a considerable deficit in the anticipated solar PV energy yield.[33] Optimization techniques are employed to maximize the solar irradiation impinging on a tilted surface, guiding the determination of the overall solar irradiation on a tilted area and average irradiation on a horizontal surface for the selected Iraqi locations.[34]

Tilt Angle-Latitude Relations

In the installation of solar PV systems within Iraq, it is recognized that their power output is maximized when they are orientated to receive direct sunlight at a 90° angle. The PV module's surface tilt angle is contingent upon the geographic specifics of the installation site, such as the local latitude. In the study, it was determined that the range of optimal tilt angles varies from a minimum of 28,3 degrees in the province of Basrah to a maximum of 34,5 degrees in the province of Dohuk, relative to the horizon.[35] It has been noted that an increase in the latitude of the site necessitates a corresponding elevation in the surface tilt angle to harness optimum solar radiation.[36]

Extensive analyses of the relationship between latitude and optimal tilt angle have been conducted. These relationships often serve as heuristic guidelines for solar PV installers across various sites. While providing a rudimentary and approximate tilt angle, precise optimization for a particular site demands calculation based on local solar irradiation data. Latitude-based formulas for the optimal tilt angle do not account for influential factors such as elevation above sea level or patterns of cloud coverage, rendering them less accurate for regions with prevalent cloudiness, such as Northern Europe. The veracity of these relations varies by location, yet they are commonly employed within the PV industry for system installation.[37]

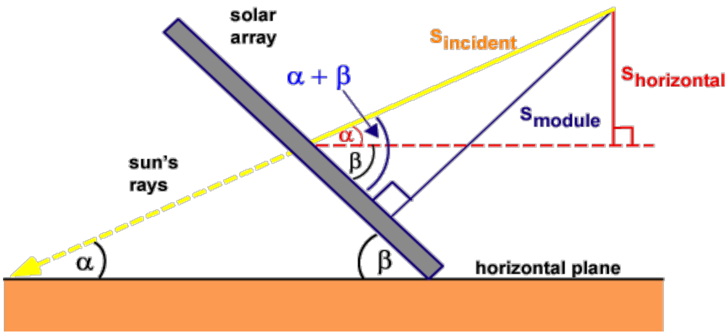

Figure 2. Tilting the module to the incoming light reduces the module output[35]

Table 3. Optimum Tilt Angle relations with respect to altitude in the previous research

Year	Location	Optimum Tilt Angle with respect to altitude	Ref.
2014	Romania	$\beta_{opt}=\varphi-\delta$	(38)
2013	Ghana	$\beta_{opt}=\varphi+17°$	(39)
2012	EightprovincesofTurkey	$\beta_{opt}=34,783-1,4317\delta-0,0081\delta^2+0,0002\delta^3$	(40)
2011	Ontario,Canada	*Yearly*, $B_{opt}=\varphi$	(41)
2011	Ottawa & Toronto,Canada	*Yearly*, $B_{opt}=\varphi-(7\rightarrow12°)$	(41)
2011	UnitedStates	$\beta_{opt}=\varphi-(1°-10°)$	(42)
2011	Iran	$\beta_{opt}=0,917\varphi \pm 0,321°$	(43)
2011	Madinah,SaudiArabia	*Yearly*, $B_{opt}=\varphi$	(44)
2009	NewDelhi,India	*Summer*; $B_{opt}=\varphi-60°$; *Winter*; $B_{opt}=\varphi+90°$	(45)
2009	USAandEurope	$\beta_{opt}=\varphi-(26°,27°,28°)$	(46)
2007	Izmir,Turkey	*SummerorWinter* $\beta_{opt}=\varphi\pm15°$ *Mar.& Sep.*; $\beta_{opt}=\varphi$	(47)

https://doi.org/10.56294/sctconf2024871

The ideal orientation for solar arrays is commonly southward in the northern hemisphere, with the optimal tilt angle being primarily a function of the local latitude. Khadim et al.(35) have postulated that it has been observed that the annual variation in optimal inclination angles for Iraq's provinces, in relation to the horizon for solar panels, consistently shows a range of 2 to 3 degrees between latitudes as shown in figure 2. Additionally, the monthly optimal tilt angles across these provinces exhibit a variation ranging from 1 to 8 degrees. Thus, it is concluded that the optimal tilt angle for any location in Iraq lies within a spectrum of 28,3 to 34,5 degrees relative to the horizon.

RESULTS AND DISCUSSION

It is asserted that the solar module's optimal tilt angles are variable, contingent on the Sun's monthly and seasonal trajectories. For Iraq, the derived optimum monthly and seasonal tilt angles, as extrapolated from various studies, are elucidated herein. Subsequently, a comparative analysis is conducted between the outcomes yielded by the utilization of a tilted surface and a horizontal plane at these optimal tilt angles, thereby evaluating the effectiveness of the tilt angle optimization.

IV Optimization Tilt Angle

In 2020, Yunus Khan et al.[4], has been demonstrated that the collection of maximum solar radiation is achievable through tilt angles ranging from 0° to 64°. In this range, the optimum angle is determined by searching for the maximum total hourly-daily irradiance values, with a resolution of 1°.

As shown in figure 3, the steepest tilt angles are achieved in January, November, and December. Conversely, a reduction in the optimal tilt angle, by approximately 10°, is observed in February and October, aligning with the local latitude angle in March. A similar trend is reported in two locations, with a notable difference in the January tilt angle. The highest and lowest tilt angles were reported in analogs to Erbil and Anbar, respectively.

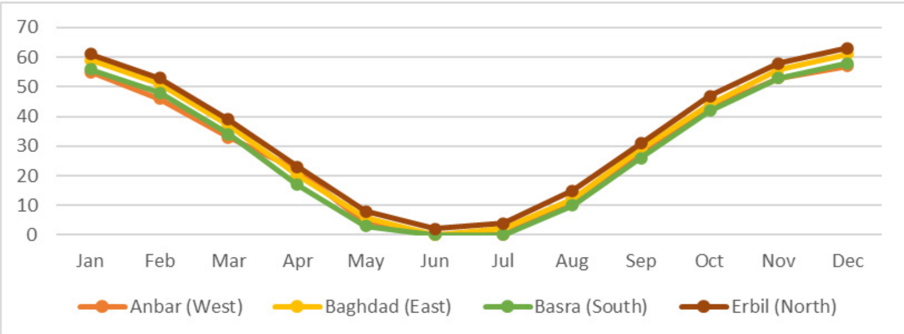

Figure 3. Finest tilt angle vs. month for five locations in Iraq

The tilt angle values typically peak from November to January and at year's end before declining towards April through September, where a zero tilt angle is optimal for all zones, similar to observations in other locales. For Erbil, the optimal monthly tilt angle, depicted in table 4, diminishes by nearly 10° in February and October.

Table 4. Different titled surface in eighteen governorates of Iraq based on the different tilt angle

Governorate	ß optimum (yearly)	Latitude	+15 Latitude	−15 Latitude
Anbar	2127,74	2119,66	2119,18	2120,07
Babylon	2056,7	2050,66	2050,36	2051,06
Baghdad	2035,66	2032,35	2032,03	2032,63
Basra	2010,7	2006,06	2005,73	2006,38
Dhi Qar	2064,32	2060,52	2060,23	2060,83
Diyala	2041,38	2038,1	2037,81	2038,36
Duhok	2007,33	2001,35	2000,89	2001,69
Erbil	2006,32	1999,56	1999,17	1999,95
Karbala	2063,98	2058,2	2057,85	2058,59
Kirkuk	2047,9	2042,58	2042,2	2042,95
Maysan	2081,13	2078,93	2078,67	2079,16

Muthanna	2057,68	2051,91	2051,56	2052,36
Najaf	2050,56	2044,21	2043,81	2044,56
Nineveh	2010,56	2003,95	2003,55	2004,37
Qadisiyyah	2074,73	2065,98	2065,48	2066,44
Saladin	2047,49	2040,34	2039,95	2040,78
Sulaymaniyah	2025,66	2020,44	2020,03	2020,08
Wasit	2082,43	2079,04	2078,69	2079,31

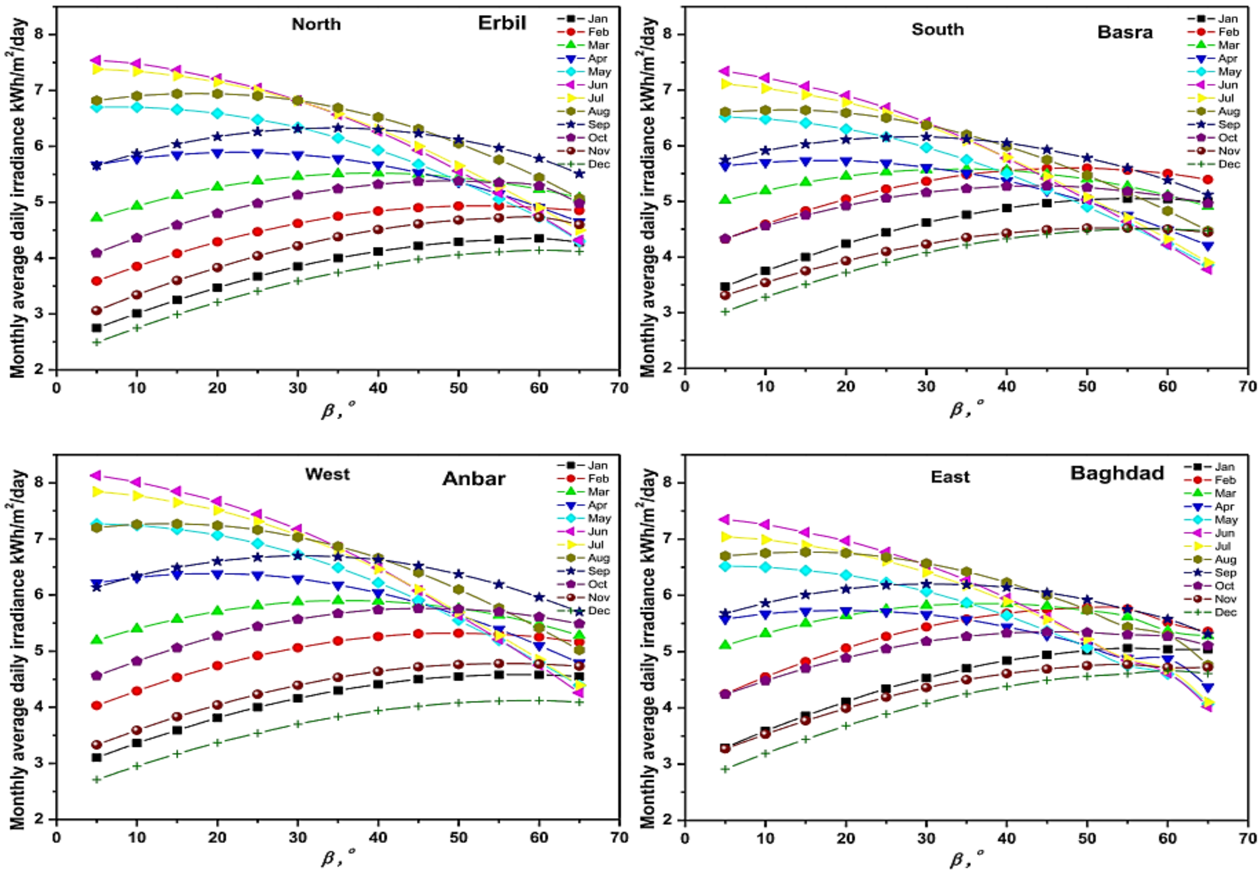

Figure 3. Accessibility of the monthly average daily solar irradiance of tilted surfaces for four provinces of Iraq

The Earth travels around the sun in an elliptical path, completing a circle every 365,25 days. This orbit, crucial for harnessing solar energy, remains constant. The sun, rising in the east and setting in the west, peaks around noon. The solar declination δ, as illustrated in the figure 4, is the angle between the equator's plane and a line from the sun's center to Earth's center. On the summer solstice, June 21, the sun is at its zenith. A ray from the sun to Earth forms a 23,45° angle with the equator, shining directly over the Tropic of Cancer at 23,45° latitude. Equinoxes see the sun above the equator. On December 21, the winter solstice, the sun is 23,45° south of the equator, over the Tropic of Capricorn. Understanding Earth›s declination angle, which fluctuates between ±23,45°, is key for optimal solar panel positioning. This angle, modeled by a sinusoidal equation assuming a 365-day year and placing the spring equinox on the 81st day, is crucial for calculations. The equation for determining this angle follows:

$$\delta = 23.45^\circ \; sin\, sin\, (360/365\,(n - 81)) \quad \textbf{(6)}$$

The n is the nth day of the year.

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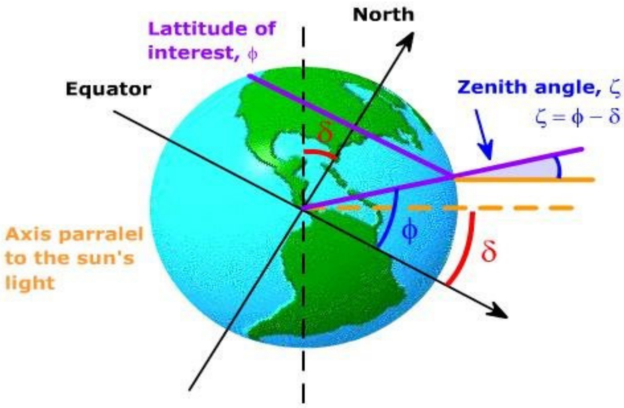

Figure 4. The solar declination δ the angle between the sun and the equator[43]

Figure 5 presents the monthly average daily solar radiation for the monthly and yearly determined optimum tilt angles, including variations of ±15° latitude. A general model has been developed to determine the optimum tilt angle positioning for maximum incident solar radiation in four Iraqi governorates located in the north, south, east, and west (as depicted in figure 3). Table 4 displays the annual expected incident solar radiation in the 18 Iraqi governorates, based on the adjusted tilt angles (yearly, latitude°, +15° latitude, and −15° latitude).

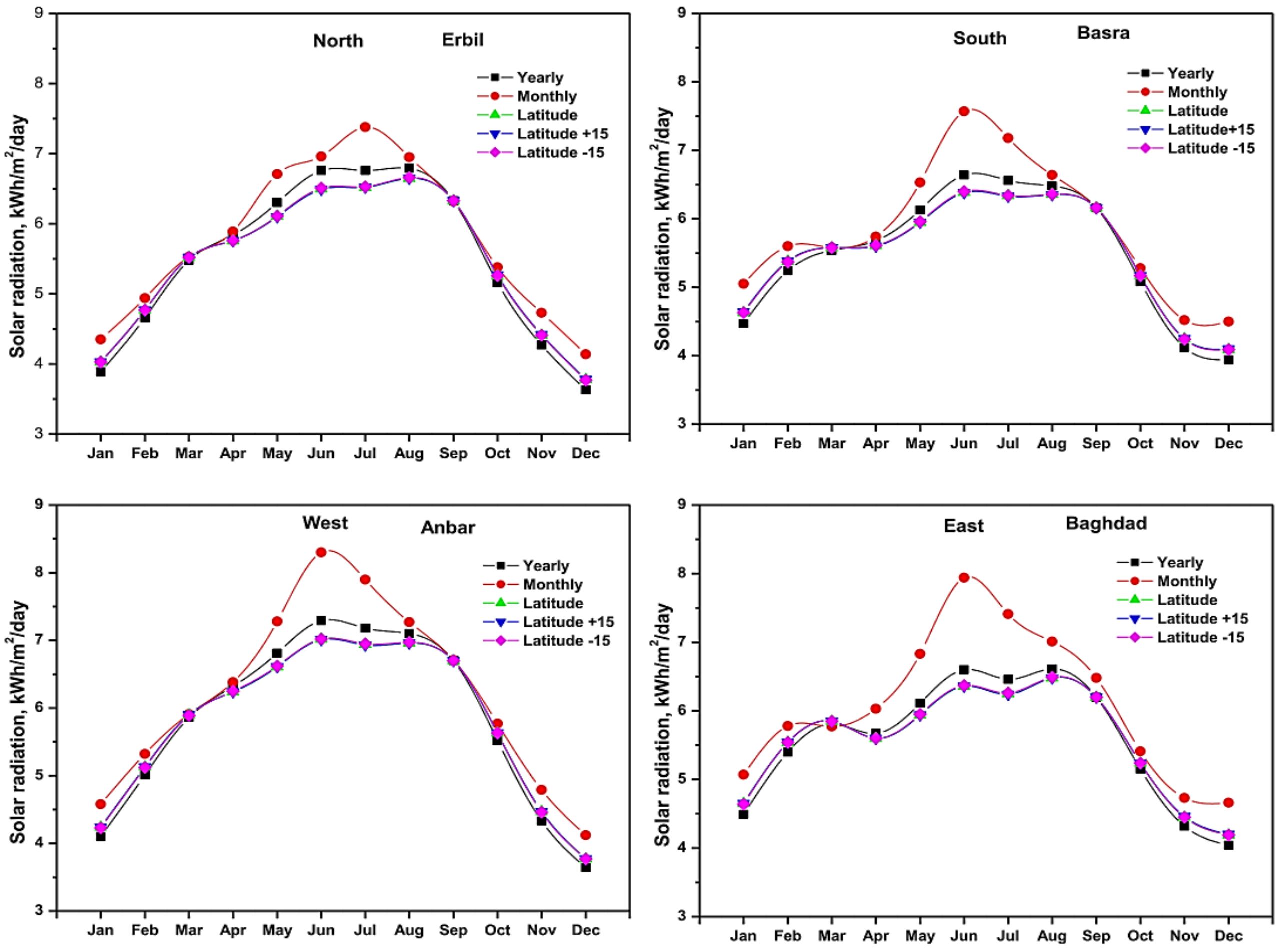

Figure 5. The monthly average daily solar irradiance at the determined tilt angles for four provinces of Iraq

The most significant losses were recorded in the western governorates (Anbar: 8,08 kWh/m², 0,38 %; Qadisiyyah: 8,75 kWh/m², 0,42 %), while the eastern governorates exhibited lesser values (Baghdad: 3,31 kWh/m², 0,16 %; Diyala: 3,28 kWh/m², 0,16 %; Maysan: 2,2 kWh/m², 0,12 %; Waist: 3,39 kWh/m², 0,16 %).

CONCLUSIONS

It has been concluded that the precise determination of a photovoltaic (PV) panel's optimal tilt angle is crucial for its efficient operation, as imprecise alignment results in diminished solar power collection. The process of calculating these optimal tilt angles is founded on the principle of maximizing solar irradiation on a tilted surface, utilizing various optimization methods.

- It is observed that, compared to panels with a fixed slope, those with seasonal adjustments can harvest up to 40 % more solar energy.
- For Iraq, the ideal tilt angle has been established at 38 degrees.
- Seasonal adjustments of the optimal tilt angles for Anbar, Baghdad, Erbil, and Basra lead to increased energy yields of 5,02 %, 5,03 %, 5,65 %, 6,13 %, and 7,96 % respectively. In contrast, monthly adjustments in these same regions result in yield increases of 4,58 %, 4,54 %, 5,70 %, 5,85 %, and 4,11 % respectively.
- It is emphasized that the tilt angle of a solar panel must be precisely set to ensure maximum solar irradiation absorption and to prevent any partial shading.

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FINANCING

There is no specific funding to support this research.

CONFLICT OF INTEREST

All authors reviewed the results, approved the final version of the manuscript and agreed to publish it.

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https://doi.org/10.56294/sctconf2024871