Optimization of The Tilt Angle of Solar Panels for Six Cities in Iraq

Afrah A. J. Qali*, Ayse Inan*, Hidir Duzkaya*‡

*Department of Electrical-Electronics Engineering, Faculty of Engineering, Gazi University, Ankara 06570, Turkey

(afrah.a.qali@gmail.com, ayse.inan@gazi.edu.tr, hduzkaya@gazi.edu.tr)

‡Corresponding Author; Hidir Duzkaya, Department of Electrical-Electronics Engineering, Faculty of Engineering, Gazi University, Ankara 06570, Turkey, Tel: +90 312 582 3313, Fax: +90 312 221 32 02, hduzkaya@gazi.edu.tr

Received: 27.02.2024 Accepted: 04.06.2024

Abstract- Endowed with significant solar energy potential, Iraq must undertake strategic measures to address the escalating energy demands. The efficacy of photovoltaic (PV) panels is intricately tied to the inclination angle; hence, ensuring the optimal tilt angle is imperative for maximizing PV panel energy output. This study utilizes the PVGIS simulation tool to predict the maximum energy production of solar energy systems in different cities in Iraq. Simulation results, considering factors such as latitude, tilt angles, and energy production, provide predictions for these cities' monthly, seasonal, and annual energy production. The results show that the maximum energy production in all cities, depending on the angle of impact of the sun's rays, is achieved between March and October at low tilt angle values. Although energy production is low in the winter period, it can be increased by increasing the optimum tilt angle value. With seasonal and monthly tilt angle changes, annual energy production can be increased from 4.30% to 5.43% in all cities. Ramadi has the highest electricity production in all optimum tilt angle selection scenarios covering different periods. Basrah and Baghdad follow this city. Zakho, Mosul, and Kirkuk have the lowest electricity production in the country's north. These results underscore the importance of selecting the optimal location and tilt angle for installing solar energy facilities to accurately assess the solar energy potential of Iraq and its surrounding countries.

Keywords Photovoltaic (PV); energy production; optimum tilt angle; PVGIS.

1. Introduction

Solar power is a green energy solution available globally. Some countries are located in or near the solar belt, experiencing prolonged periods of sunlight, which results in high insulation levels. These places are ideal for utilizing solar technologies [1]. The sun's estimated lifespan is still five billion years, making it an inexhaustible and renewable energy source on our timescale. The total energy obtained from the Earth's surface is 720 million TWh annually, 6000 times the primary consumption of all human activities. However, the availability of this energy depends on the day-night cycle, the latitude where the power is captured, the seasons, and the cloud cover [2]. Photovoltaic (PV) cells, also known as solar cells, are constructed from unique semiconductor materials, such as silicon, which is currently the most commonly used. When sunlight strikes the solar cell, some of this solar energy is absorbed into the semiconductor material [3]. This absorbed energy within the semiconductor then dislodges electrons, enabling them to move freely. This movement of electrons constitutes an electrical current. The resulting current, in conjunction with the cell's voltage (generated by its built-in electric field or fields), determines the power (or wattage) that the solar cell can produce [3].

The panels' tilt and azimuth angles directly impact the operation of any photovoltaic system. This is because alterations in these angles influence the amount of solar radiation reaching the panel surfaces [4]. The proportion of solar energy to the total energy generated globally and in Turkey between 2018 and 2022 is as follows: In 2018, the total energy generated worldwide amounted to 26,174.37 TWh. By 2022, this figure reached 28,660.98 TWh. In Turkey, total energy production increased from 303.86 TWh in 2018 to 326.11 TWh by 2022 [5]. Many studies indicate that the optimal tilt angle varies depending on the latitude, solar altitude angle, or day of the year [6].

Baghel, Manjunath, and Anil [7] state in their research that PVsyst 7.2.11 is a comprehensive software tool for planning and modeling solar PV systems. Depending on the site's latitude, adjusting the tilt angle and enhancing the albedo can boost the solar PV system's performance. Installing such a system reduces CO_2 emissions, promotes environmental sustainability, and increases the potential for claiming carbon credits.

Jing et al. [8] utilized the hourly solar radiation model by Collares-Pereira and Rabl, as well as the model for solar radiation on sloped surfaces. Focusing on China's solar energy resources, the study examined their spatial distribution and determined the optimal tilt angle and energy production potential of PV systems. The findings reveal that China experiences annual global solar radiation ranging from 3097 MJm^2 to 7311 MJm^2, with annual diffuse solar radiation values spanning from 495 MJm^2 to 3036 MJm^2. The optimal tilt angle in different regions of China is found to vary between 14.5° and 49.1°, generally following a pattern of increasing angle with latitude. The annual photovoltaic energy production ranges from 117 $kWhm^2$ to 483 $kWhm^2$.

Ibrahim and Ibrahim [9] assessed the influence of the tilt angle on the harvested solar energy and the energy output of a photovoltaic system concerning their expenses utilizing HOMER software. The findings confirmed that the most effective yearly tilt angle in Duhok, Iraq, is 25°.

Hassan et al. [10] aim to assess the solar energy potential in Iraq and determine the optimal tilt angles for maximum solar irradiance in their studies. The optimal tilt angles facing south for eighteen cities have been determined using nineteen years of experimental solar radiation data. The results indicate that maximum solar irradiance can be collected with tilt angles ranging from 0° to 64°. The optimal tilt angles increase during the winter months and decrease during the summer months. Northern cities exhibit higher optimal tilt angles than those in the central and southern regions.

Wessley, Narciss, and Sandhya [11] calculated the optimum tilt angle for eight cities across India. Solar radiation received at various tilt angles, ranging from 1° to 90°, has been simulated, and the annual optimum tilt angle has been determined for all cities. Based on the results of this study, a mathematical correlation is proposed to estimate the optimum tilt angle of any town in India based on its latitude. Al-Nimr and Al-Shohani [12] analyzed the solar energy output of Iraq's three locations (Mosul, Baghdad, and Al-Hammar lagoon) using solar radiation and ambient temperature data. Jallo [13] evaluated the feasibility of using solar PV electricity in residential homes in Iraq. The researcher concluded that Iraq has remarkable potential for electricity generation through PV systems and that the PV system offers an attractive alternative for improving household life within the country. Al-Waeli and Al-Asadi [14] analyzed the use of standalone PV systems in the Iraqi desert. The results showed that the system could provide the necessary energy for citizens in the desert.

In Iraq, there is a growing demand to install solar energy systems in residential areas due to high electricity prices and the goal of reducing dependence on local energy producers. This study evaluates energy production and the optimum tilt angle on a monthly, seasonal, and annual basis for Iraq's southern and northernmost cities using the PVGIS simulation tool. These simulations demonstrate that electrical energy production can be increased by adjusting the PV panel angles, traditionally set according to the longitude angle, to seasonal and monthly optimum tilt angles. Similar PVGIS-based analyses conducted for seven different cities in Türkiye have also shown that replacing a single latitude-based tilt angle with seasonally or monthly adjusted optimum tilt angles can increase annual energy production by approximately 4–5% [15].

2. Calculation Methods

PVGIS helps predict the monthly and annual electricity production of a solar energy system, based on the specified panel tilt and orientation (in kWh). Users can also access radiation maps for various countries and regions for free [16]. Data retrieval from PVGIS-SARAH2 can be directly accomplished through a web application available at the photovoltaic geographical information system, which is suitable for single-location usage [17]. This includes the latitude and longitude coordinates of the selected locations, as determined using the Solar Radiation Database (PVGIS-SARAH2). Photovoltaic technology is chosen as crystalline silicon, and the mounting method is set to fixed mounting. The optimum tilt angle ranges from 0 to 90º for all cities. The azimuth or orientation is 0 degrees, and an installed power of 1 kW is employed. The PV tilt angle refers to the angle at which the solar panels are installed in relation to the horizontal plane. An angle of 0° is associated with horizontal, and an angle of 90° is associated with vertical. The PV azimuth angle refers to the direction in which the PV panels are facing. South is 0°, east is -90 °, west is +90°, and north is 180° as determined. In optimum fixed-azimuth setups, the panels are practically oriented toward the equator [18].

PVGIS computes the impact of irradiance and module temperature by employing a model outlined in. The power is presumed to be contingent on irradiance (G) and module temperature (T_m) in the subsequent manner [17]:

$$P = G/1000 * A * eff(G, T_m) = G/1000 * A * eff_{nom} * eff_{rel}(G, T_m) \quad (1)$$

$$eff_{rel}(G', T'_m) = 1 + k_1 \ln(G') + k_2 \ln(G')^2 + k_3 T'_m + k_4 T'_m \ln(G') + k_5 T'_m \ln(G')^2 + k_6 T'^2_m \quad (2)$$

where $G' = G/1000$, and the coefficients k_1 to k_6 are determined for each PV technology through fitting to measured data. The module temperature T_m can be determined as:

$$T_m = T_a + G/(U_0 + U_1 W) \quad (3)$$

where T_a is the air temperature, and W is the wind speed [19]. The coefficients utilized in PVGIS are derived from measurements conducted at the European Solar Test Installation (ESTI).

Abo-Zahhad et al. [20] utilized PVsyst, power estimation methods based on ANSYS, and practical formulas to assess the effectiveness of PV systems. Meteorological data from Meteonorm 8.1, PVGIS, and NASA-SSE satellite data are incorporated. The findings revealed notable differences in the predicted energy output depending on the weather data source. PVGIS overestimations varied from 7.7% to 13.5% compared to NASA-SSE satellite data, and Meteonorm 8.1 overestimations ranged from 2.5% to 6.7%. Complementary to such simulation-based assessments, deep learning-based solar irradiance forecasting studies for Cameroon have demonstrated that advanced time-series models can significantly enhance short-term prediction accuracy, thereby supporting the reliable operation of PV systems under diverse climatic conditions [21].

Tarai and Kale [22] discuss the utility of developing a strategy to promote grid-connected PV system installations on a regional basis using the PVGIS online software, specifically for Odisha, India. The potential for PV energy in the entire Odisha region with an independent system ranges from 1300 kWh/kWp to 1550 kWh/kWp for a fixed PV system and from 1510 kWh/kWp to 2030 kWh/kWp for a PV system equipped with a two-axis tracking system. The percentage of high-potential areas increases when fitted with a two-axis tracking PV system.

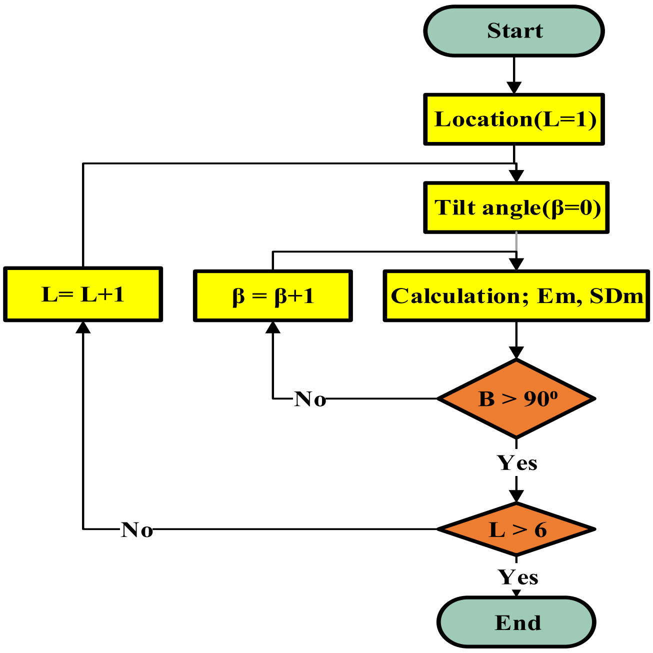

Fig. 1. Flowchart of simulation in PVGIS.

Kassem et al. [23] simulated a 6.4 kW PV system with various PV technologies and sun-tracking systems using the PVGIS simulation tool to predict energy production in Iraq's weather conditions. The solar radiation data indicated that the chosen city is well-suited for potential PV system installations. Additionally, the findings affirmed that CdTe technology outperforms crystalline and CIS PV technologies in terms of performance. Furthermore, the two-axis system demonstrated the highest energy generation compared to vertical and inclined systems.

The flowchart in Figure 1 is used in the PVGIS calculations for this study. According to this flow diagram, the first step is to select the city. Then, the energy production and its standard deviation are calculated by varying the tilt angle of the panels from 0° to 90°.

3. Results and Discussions

In this study, six cities along the north-south axis are selected to characterize the entire country of Iraq. The locations and regions of these cities on the Iraq map are shown in Figure 2. The weather conditions in the selected cities are described as cold and humid in winter and scorching and dry in summer [24].

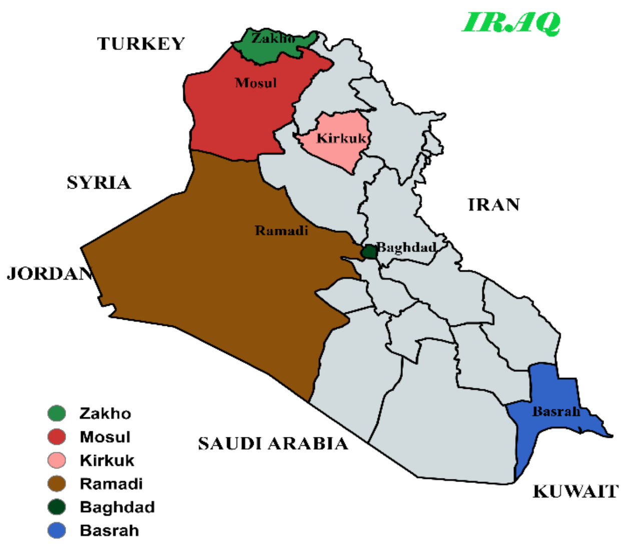

Fig. 2. Map of Iraq for the studied regions.

PVGIS is an online simulation tool designed to estimate the energy yield of photovoltaic (PV) systems. Moreover, it offers an extensive and precise global database of solar radiation. Numerous scientific researchers have employed the PVGIS simulation tool to assess the potential energy production of PV systems. In a particular study focusing on Baghdad, the optimal tilt angle (β_{opt}) during the winter season was determined to be 56°, considering the city's latitude of 33.32'. Conversely, the optimal tilt angles for summer are 6° and 7° [25]. The findings obtained through an empirical model in previous studies indicate that, for Baghdad, the ideal tilt angle for solar panels to receive maximum insulation during winter is approximately 54°; this is equivalent to a latitude angle of +20°. On the other hand, during summer, when maximum radiation falls almost horizontally, the optimal tilt angle is approximately 12°, indicating a deviation of the latitude angle by -20° [25]. In another study, a 6.4 kW PV installation incorporating various PV technologies and solar tracking systems was processed using the PVGIS simulation tool to measure energy output in Iraq's climate conditions. Based on solar radiation data, it was recognized that the selected city offered the potential for future PV system installations. Moreover, the findings proved that CdTe technology outperforms crystal and CIS PV technologies [23]. In other research, they calculated the optimal tilt angles for solar collectors by analyzing the monthly average daily solar radiation on a flat surface in several urban areas of Iraq, including Mosul, Rutba, and Basra. Their findings indicate that during the winter, solar collectors can be placed at high angles to capture the highest solar radiation. Conversely, during the summer, they can be set at medium angles and mounted at low angles to ensure the best absorption of sunlight by the solar antenna [26].

Hafez et al. (2017) work aims to review different techniques for optimizing the angle of inclination and examine the effects of different components of solar radiation (direct beam, diffuse, and reflected from the ground) on design performance. Theoretical concepts and calculations have been made in various solar systems with different factors and locations. The solar radiation models mentioned above have been applied using various models, primarily the Liu and Jordan models, to calculate the average daily solar radiation on an inclined surface to determine the optimum tilt angle [27].

Despotovic and Nedic (2015) determined the optimum tilt angles of solar collectors for Belgrade, Serbia at annual, semester, seasonal, monthly, biweekly, and daily levels. The appropriate tilt angles for the collection devices oriented towards the equator have been calculated. Four different seasonal scenarios and two different semester scenarios were considered. The energy per square meter has been compared for ten different scenarios. No significant energy difference per square meter was determined when placed at the optimal daily, biweekly, or monthly tilt angles. Although the seasonal optimal tilt angles vary depending on the definition of the season, the amount of energy collected is similar for all seasonal scenarios. Significant differences were observed in the semester scenarios. When the slope angles are adjusted twice a year, the amount of energy collected is quite low when the slope angles are adjusted on January 1 and July 1. The case study of the buildings used in the simulation showed that the energy gains of the panels placed at the optimal annual, seasonal, and monthly slope angles increased by 5.98%, 13.55%, and 15.42% compared to the panels fixed to the existing roof angles. These show that changing the angles at which the collectors are installed on the roof is useful, at least at a seasonal level (twice a year) [28].

Bakirci (2021) investigated horizontal DSR prediction models for Turkey. The most suitable of these models can be used in regions with similar climatic conditions, where DSR measurements are unavailable. The study examined 31 models developed to predict the monthly average daily DSR in the horizontal plane. These DSR models were tested using meteorological data from two sample stations in Turkey, such as Erzurum and Gebze. The models are divided into six categories based on input variables such as the aperture index and the relative duration of sunbathing. These variables include data such as extraterrestrial radiation, total radiation, isolation time, and maximum possible isolation time. Various statistical test techniques have evaluated the performance of the models, these techniques include measurements such as root mean square error (RMSE) and mean absolute error (MAE). Statistical comparisons show that the best models are compatible with the DSR values obtained from NASA-SSE. The differences between the annual total DSR calculated with the best models and NASA-SSE are approximately 1.94% for Erzurum and 0.57% for Gebze [29].

Oliveira-Pinto and Stokkermans (2020), Floating solar technology FPV appeared about ten years ago due to the increasingly intensive use of large-scale ground-based PV plants and the loss of efficiency at high operating cell temperatures. It aims to close the difference between the expected improved performance of FPV systems in the literature and the results of the energy efficiency assessment conducted by PVsyst.Dec. The findings show that performance varies significantly depending on technology and location. The economic suitability of FPV technologies and internal reference systems has been analyzed. Despite having lower advanced performance, FPV systems are economically attractive solutions. The increase in production due to FPV technologies varies between 0.31% and 2.59% depending on floating solar technologies and shows that it is below the values predicted in the literature (Dec. 10%). The adjusted level of energy cost varies between € 96.2/MWh and € 50.3/MWh, depending on the technology and the solar radiation reaching the site [30].

Hassan (2021) aims to evaluate the solar energy potential in Iraq and determine the optimal inclination angles for maximizing solar radiation. The best south-facing tilt angles for eighteen cities have been determined to estimate solar radiation capacity. The best tilt angles were determined by an optimization process performed using nineteen years of hourly experimental solar radiation data. The results show that the maximum solar radiation can be collected from the Declivity angle between 0° and 64°. The optimum angles were determined by investigating the maximum hourly-daily radiation values with a resolution of 1°. December, June, January, and July Optimum slope angle values increased in winter and decreased in summer; the highest values in all provinces were observed in January and December, and the lowest in June and July. Cities in the north of Iraq have higher optimal tilt angle values than cities in the middle and south [10]. The geographical latitude and longitude values of the cities examined in this study, the tilt angle chosen according to latitude and the annual energy produced according to this tilt angle value are presented in Table 1.

According to the results of the PVGIS simulation in these cities, the optimum tilt angles for maximum energy production and the annual energy production obtained with these angles are summarized in Table 2. These annual optimum tilt angle values differ from traditionally used latitude angle values, and this causes increases in energy production.

Seasonal optimum tilt angle values to produce more energy from PV panels in these cities and the energy produced seasonally under this condition are shown in Table 3. Optimum tilt angle values during the winter vary between 54º-59º. This value is more than 20º according to annual optimum tilt angles. Optimum tilt angles during the spring vary between 20º-24º. This value is lower than 10º according to annual optimum tilt angles. Optimum tilt angles during summer vary between 4º-10º degrees and are approximately 25º lower than the annual optimum tilt angle values. In the autumn, optimum tilt angles vary between 41º-47º and are approximately 10º higher than the annual optimum tilt angle values.

If the optimum tilt angle is changed seasonally, the lowest energy production for all seasons is in Zakho, and the highest is in Ramadi. The main reason is that solar radiation spread is low in the northern regions of Iraq, and the highest spread is observed in the city of Ramadi. The difference between the

Table 1. Geographical latitude and longitude positions of the cities

	Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
Latitude	30.50'	33.32'	33.42'	35.46'	36.34'	37.13'
Longitude	47.81'	44.42'	43.30'	44.39'	43.13'	42.69'
β (º)	30º	33º	33º	35º	36º	37º
EP (kW)	1642.21	1640.03	1692.27	1588.45	1585.88	1519.70

Table 2. Annual optimal PV panel tilt angles and energy productions

	Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
Annual β_{opt}	30º	32º	32º	32º	33º	33º
Annual EP (kWh)	1642.21	1640.41	1692.52	1589.81	1587.84	1522.91

Table 3. Seasonal optimal PV panel tilt angles and energy production potentials

		Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
Winter	β_{opt}	54º	56º	56º	58º	58º	59º
	EP (kWh)	384.57	373.02	390.57	331.72	321.31	294.21
Spring	β_{opt}	20º	22º	22º	23º	24º	23º
	EP (kWh)	428.31	435.1	446.12	421.73	424.5	401.62
Summer	β_{opt}	4º	6º-7º	6º-7º	8º	9º	9º-10º
	EP (kWh)	484.22	494.67	508.42	501.5	502.55	498.67
Autumn	β_{opt}	41º	44º	44º	46º	46º-47º	47º
	EP (kWh)	415.82	409.8	423.18	402.88	406.87	393.32

seasonal energy production potentials of Zakho and Ramadi cities, where the lowest and highest energy can be produced, is 32.75%, 11.08%, 1.95%, and 7.59% in the winter, spring, summer, and autumn periods, respectively. According to these cities' seasonal optimum tilt angles, there is a difference between 25.91% and 69.49% in terms of energy production potential between summer and winter. While this difference between the summer and winter periods is less in the southern cities, it exceeds 50% towards the north. The energy production potentials of the cities examined within the scope of the study, according to the seasonal optimum tilt angle, are shown in Figure 3. While the energy production potential of all cities becomes closer to each other in the summer, dramatic differences are observed in the winter due to latitude differences.

The monthly optimum tilt angle (β_{opt}) and energy production potential of PV panels for maximum energy production in these cities are presented in Table 4. The highest optimum tilt angles are observed in winter, especially in December. The values of optimum tilt angles from south to north in December vary between 58º and 64º. The lowest optimum tilt angles are observed in summer, especially in June. In June, the values of optimum tilt angles from south to north vary between 0 and 3º. The highest monthly energy production potential is in Ramadi, except for October and December, and in Basra in these months. The lowest monthly energy production potential is in Basrah between May and September, and in Zakho between October and April.

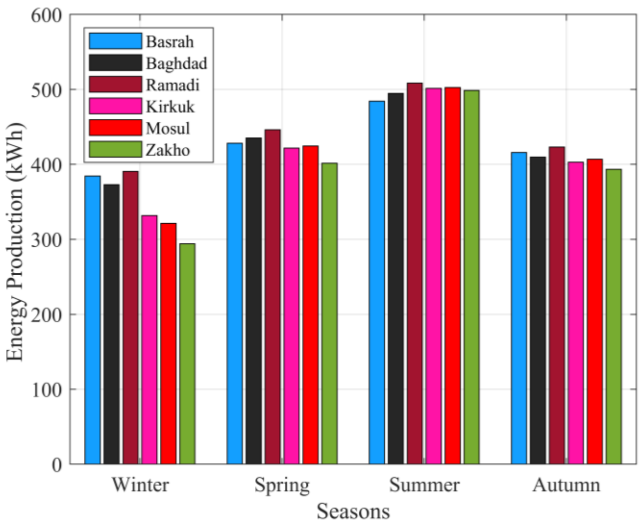

Fig. 3. Seasonal optimal tilt angles for PV panels and energy production potentials.

Table 4. Monthly optimal tilt angles and energy production potentials

		Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
January	β_{opt}	55º	58º	58º	59º	60º	61º
	EP (kWh)	126.95	124.24	131.22	108.9	104.34	95.99
February	β_{opt}	47º	49º	50º	51º	51º	52º
	EP (kWh)	126.72	123.1	129.38	109.37	109.44	96.99
March	β_{opt}	34º	37º	37º	38º	39º	38º
	EP (kWh)	147.14	144.41	148.91	132.94	132.88	120.89
April	β_{opt}	18º	21º	21º	23º	23º	23º
	EP (kWh)	137.54	142.03	145.25	139.17	139.09	131.61
May	β_{opt}	5º	7º	7º	9º	9º	10º
	EP (kWh)	150.27	155.56	159.09	155.89	158.97	154.88
June	β_{opt}	0º	0º	1º	2º	2º	3º
	EP (kWh)	164.83	167.53	171.11	170.11	170.66	167.64
July	β_{opt}	1º	3º	4º	5º	6º	6º
	EP (kWh)	162.67	167.77	173.51	169.77	170.41	169.71
August	β_{opt}	13º	16º	16º	18º	19º	19º
	EP (kWh)	158.7	161.64	166.21	164.02	164.11	163.99
September	β_{opt}	29º	32º	32º	34º	35º	35º
	EP (kWh)	152.63	152.44	155.87	153.27	154.37	153.34
October	β_{opt}	43º	45º	46º	47º	48º	49º
	EP (kWh)	142.55	134.27	138.65	131.38	135.24	129.21
November	β_{opt}	54º	56º	57º	58º	58º	59º
	EP (kWh)	125.69	128.22	133.97	123.17	122.03	115.34
December	β_{opt}	58º	60º	61º	62º	63º	64º
	EP (kWh)	131.89	126.67	130.99	114.42	108.45	102.2

Although the city of Basrah is located in the south of the country, it is believed that the reason for its lowest energy production potential between May and September is the effect of dust particles and humidity. The difference between July and February, which has the highest and lowest energy production potential in Ramadi, is 34.11%. In Zakho, the difference between July and January, which has the highest and lowest energy production potential, is 76.80%. The difference between the cities with the highest and lowest energy production in June and July, when the energy production potential is at its peak, is 3.81% and 6.66%, respectively. In January, when there is the least potential for energy production, the difference between the cities with the most and least energy production is 36.70%. The monthly optimum tilt angle changes for Baghdad, Basrah, and Mosul, the three cities with the highest populations in the country, are shown in Figure 4.

The annual, seasonal, and monthly energy production potential, as calculated within the scope of this study, along with the changes in energy production according to the traditionally preferred latitudinal tilt angle, are presented in Table 5. The cities with the highest and lowest energy production potential for all tilt angle selection methods are Ramadi and Zakho, respectively. If annual and latitudinal tilt angles are used, no difference is observed for the southern cities, while an increase of up to 0.21% is observed in the northern cities. If the use of seasonal tilt angle in PV panels is preferred, the energy production potential increases between 4.30% and 4.49%. If the monthly optimum tilt angle is selected, the energy production potential increases between 5.20% and 5.43%. The highest increase in energy production occurs at the seasonal and monthly optimum tilt angles in Ramadi and Zakho. The difference between annual and seasonal energy production in Ramadi is 75.77 kWh/year and 91.64 kWh/year, respectively. In Basrah, the city with the lowest energy production potential due to changes in tilt angle, the differences between annual, seasonal, and monthly energy production are 70.71 kWh/year and 85.37 kWh/year, respectively.

The change in monthly energy production potential in Baghdad, Basrah, and Mosul is seen in Figure 5. Depending on the production columns, the bars defined in this way are three times the standard deviation value obtained, depending on the daily energy production change. Three times the standard deviation in these bars is chosen to indicate that 99.7% of the energy production data is distributed in this range [31].

Among these three cities, the highest standard deviation values according to daily energy production potential are observed in Mosul. The most significant changes in standard deviation values are observed in November and December. The main reason is the dramatic differences in daily energy production during winter. In addition to seasonal change, the standard deviation increases in the northern cities.

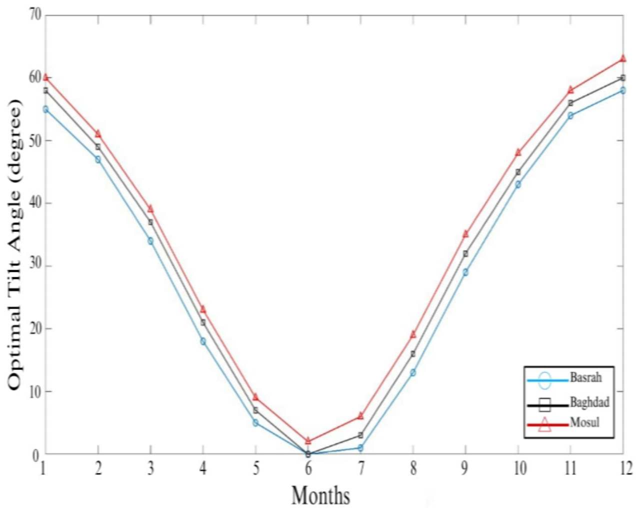

Fig. 4. Monthly optimum tilt angle changes for Baghdad, Basrah, and Mosul.

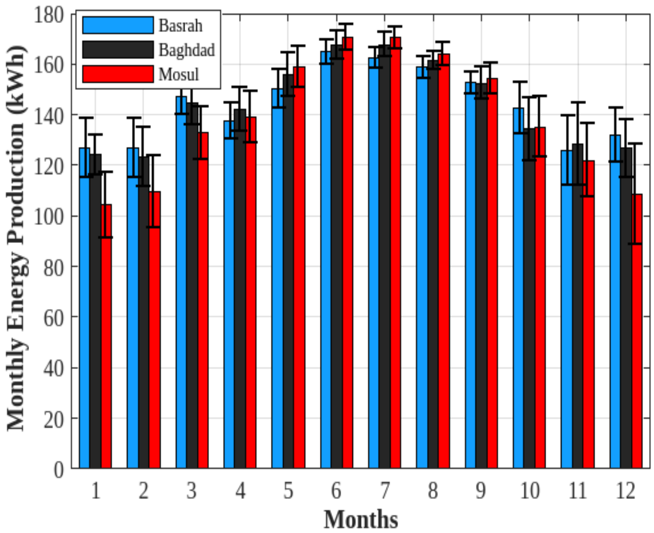

Fig. 5. Monthly energy production for Baghdad, Basrah, and Mosul.

Table 5. Energy production potentials with latitudinal, annual, seasonal, and monthly optimal tilt angles

	Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
EP (kWh) with latitude angle	1642.21	1640.03	1692.27	1588.45	1585.88	1519.70
EP (kWh) with annual βopt	1642.21	1640.41	1692.52	1589.81	1587.84	1522.91
	0.0%	0.02%	0.02%	0.09%	0.12%	0.21%
EP (kWh) with seasonal βopt	1712.92	1712.59	1768.29	1657.83	1655.23	1587.82
	4.30%	4.42%	4.49%	4.37%	4.37%	4.48%
EP (kWh) with monthly βopt	1727.58	1727.97	1784.16	1672.41	1669.99	1601.79
	5.20%	5.36%	5.43%	5.28%	5.30%	5.40%

Table 6. Annual incomes at different optimum tilt angle scenarios

	Basrah	Baghdad	Ramadi	Kirkuk	Mosul	Zakho
Annual income with latitude angle ($\$/m^2$)	65.69	65.60	67.69	63.54	63.43	60.79
Annual income with annual β_{opt} ($\$/m^2$)	65.69	65.61	67.82	63.59	63.51	60.92
Annual income with seasonal β_{opt} ($\$/m^2$)	68.52	68.50	70.73	66.31	66.21	63.51
Annual income with monthly β_{opt} ($\$/m^2$)	69.10	69.12	71.37	66.90	66.80	64.07

Annual incomes to be obtained from energy production according to latitudinal, annual, seasonal, and monthly optimum tilt angle values in the cities examined in this study are shown in Table 6. As the basis for this calculation, the electric energy price is 4 cents for households and 4.4 cents for industrial enterprises in Iraq as of June 2023 [32]. Within the scope of this study, the electricity sales price for households, 4 cents, is taken as the basis. According to annual incomes, depending on latitudinal and monthly tilt angle choices, the highest difference is 3.68 $\$/m^2$ in Ramadi, and the lowest is 3.28 $\$/m^2$ in Zakho. Considering that the average production life of PV plants is 20 years, if the optimum tilt angle is changed monthly, a total income of 65.6 $\$/m^2$ to 73.6 $\$/m^2$ can be obtained at the end of the operating life. Considering that the household electricity energy prices in the United Kingdom, Germany, France, the United States, and Turkey are 44 cents, 40 cents, 26 cents, 17 cents, and 8 cents [32], respectively, the importance of seasonal and monthly tilt angle selection in PV facilities in different geographies is better understood.

4. Conclusion

The main findings of this study, which examined the energy production depending on the latitudinal, annual, seasonal, and monthly optimum tilt angle selection of PV panels in six cities in the north-south direction in Iraq, are as follows:

- There is a deviation of up to 4^{o} between the latitude value traditionally used in panel angle selection and the annual optimum tilt angle selection. PVGIS at high latitudes increases efficiency if the same tilt angle is used throughout the year.

- Annual energy production in PV panels can increase up to 4.48% when a seasonal optimum tilt angle is used. Although energy production is less affected by the tilt angle value in the summer, it is observed that efficiency can be increased significantly, depending on the latitude, in the winter months.
- Annual energy production in PV panels can increase up to 5.43% when the monthly optimum tilt angle is used.
- Considering the electrical energy prices in Iraq, an income of up to 73.6 $/m2 can be obtained by changing the monthly optimum tilt angle until the end of the life of the PV facilities. This income may rise to non-negligible levels in developed countries with high energy prices.

This study aims to develop a model by examining parameters such as dust, humidity, and altitude that affect the efficiency of solar energy panels. Additionally, it is designed to conduct optimum tilt angle selection scenario studies by developing economic analyses in countries with high energy prices. In parallel to these economic and environmental extensions, recent SCAPS-1D based simulations of high-efficiency lead-free dual-absorber perovskite solar cells employing V_2O_5 and CdS transport layers demonstrate how detailed device-level modelling can guide material and layer selection to further enhance the overall performance of PV systems [33].

References

[1] L. Neij, “Cost development of future technologies for power generation—A study based on experience curves and complementary bottom-up assessments,” Energy Policy, vol. 36, no. 6, pp. 2200-2211, June 2008, doi: 10.1016/j.enpol.2008.02.029.

[2] B. Robyns, A. Davigny, B. François, A. Henneton, and J. Sprooten, Electricity Production from Renewable Energies, 3rd ed., Wiley, 2021, pp. 1-17

[3] R. Teodorescu, M. Liserre, and P. Rodríguez, Grid Converters for Photovoltaic and Wind Power Systems, 1st ed., John Wiley and Sons, Ltd, pp. 1-4, Dec. 2010, doi: 10.1002/9780470667057.

[4] M. A. Yakup and A. Q. Malik, “Optimum tilt angle and orientation for a solar collector in Brunei Darussalam,” Renewable Energy, vol. 24, no. 2, pp. 223-234, Oct. 2001, doi: 10.1016/S0960-1481(00)00168-3.

[5] Energy Institute, “Statistical Review of World Energy 2023,” London, United Kingdom, pp. 45-49, 2023.

[6] K. Ulgen, “Optimum Tilt Angle for Solar Collectors,” Energy Sources, Part A: Recovery, Utilization, and Environmental Effects, vol. 28, no. 13, pp. 1171–1180, Feb. 2006, doi: 10.1080/00908310600584524.

[7] N. Baghel, K. Manjunath, and A. Kumar, “Performance evaluation and optimization of albedo and tilt angle for solar photovoltaic system,” Computers and Electrical Engineering, vol. 110, no. 108849, Sept. 2023, doi: 10.1016/j.compeleceng.2023.108849.

[8] J. Jing, Y. Zhou, L. Wang, Y. Liu, and D. Wang, “The spatial distribution of China’s solar energy resources and the optimum tilt angle and power generation potential of PV systems,” Energy Conversion and Management, vol. 283, no. 116912, May 2023, doi: 10.1016/j.enconman.2023.116912.

[9] M. H. Ibrahim and M. A. Ibrahim, “Solar-wind hybrid power system analysis using Homer for Duhok, Iraq,” Przegląd Elektrotechniczny, vol. 97, no. 9, pp. 139-143, Aug. 2021, doi: 10.15199/48.2021.09.28.

[10] Q. Hassan, M. K. Abbas, A. M. Abdulateef, J. Abdulateef, and A. Mohamad, “Assessment the potential solar energy with the models for optimum tilt angles of maximum solar irradiance for Iraq,” Case Studies in Chemical and Environmental Engineering, vol. 4, no. 100140, Dec. 2021, doi: 10.1016/j.cscee.2021.100140.

[11] J. J. Wessley, R. S. Narciss, and S. S. Sandhya, “Modelling of optimal tilt angle for solar collectors across eight Indian cities,” International Journal of Renewable Energy Research (IJRER), vol. 7, no. 1, pp. 353-358, Jan. 2017, oi: 10.20508/ijrer.v7i1.4729.g6996.

[12] M. A. Al-Nimr and W. A. Al-Shohani, “Performance of photovoltaic module for different sites in Iraq,” Arabian Journal for Science and Engineering, vol. 38, no. 2, pp. 277-283, Feb. 2013, doi: 10.1007/s13369-012-0446-4.

[13] N. B. Jallo, “Should Iraqis go solar on household level?” Journal of Asian Scientific Research, vol. 3, no. 9, pp. 903-909, 2013.

[14] A. A. Al-Waeli and K. A. Al-Asadi, “Analysis of stand-alone solar photovoltaic for desert in Iraq,” International Research Journal of Advanced Engineering and Science, Vol. 3, no. 2, pp. 204-209, Jan. 2018.

[15] A. Inan, A. A. J. Qali, H. Duzkaya, and M. C. Taplamacioglu, “Optimization of the Tilt Angle of Solar Panels for Seven Cities in Türkiye,” Turkish Journal of Electrical Power and Energy Systems, vol. 4, no. 3, pp. 181-189, Oct. 2024, doi: 10.5152/tepes.2024.24013.

[16] C. S. Psomopoulos, G. C. Ioannidis, S. D. Kaminaris, K. D. Mardikis, and N. G. Katsikas, “A comparative evaluation of photovoltaic electricity production assessment software (PVGIS, PVWatts, and RETScreen),” Environ. Process, vol. 2, pp. 175–189, Aug. 2015, doi: 10.1007/s40710-015-0092-4.

[17] T. Huld, G. Friesen, A. Skoczek, R. P. Kenny, T. Sample, M. Field, and E. D. Dunlop, “A power-rating model for crystalline silicon PV modules,” Solar Energy Materials and Solar Cells, vol. 95, no. 12, pp. 3359-3369, Dec. 2011, doi: 10.1016/j.solmat.2011.07.026

[18] HOMER Energy, “HOMER Pro 3.11 User Manual,” Accessed: May 12, 2024. [Online]. Available: https://www.homerenergy.com/

[19] D. Faiman, “Assessing the outdoor operating temperature of photovoltaic modules,” Progress in Photovoltaics: Research and Applications, vol. 16, no. 4,

pp. 307–315, Feb. 2008, doi: 10.1002/pip.813.

[20] E. M. Abo-Zahhad, A. Rashwan, T. Salameh, A. K. Hamid, A. Faragalla, A. Z. El-Dein, Y. Chen, and E. H. Abdelhameed, “Evaluation of solar PV-based microgrids viability utilizing single and multi-criteria decision analysis,” Renewable Energy, vol. 221, no. 119713, Feb. 2024, doi: 10.1016/j.renene.2023.119713.

[21] R. J. J. Molu, W. F. Mbasso, S. R. Dzonde Naoussi, S. K. Tsobzé, and P. Wira, “Solar irradiance forecasting based on deep learning for sustainable electrical energy in Cameroon,” Int. J. Smart Grid (ijSmartGrid), vol. 7, no. 2, pp. 61–68, Jun. 2023, doi: 10.20508/ijsmartgrid.v7i2.279.g320.

[22] R. K. Tarai and P. Kale, “Development of rasterized Map using PVGIS for assessment of solar PV energy potential of Odisha,” International Journal of Renewable Energy Research (IJRER), vol. 6, no. 1, pp. 61-72, Jan. 2016, doi: 10.20508/ijrer.v6i1.3071.g6760.

[23] Y. Kassem, H. Gokcekus, and Q. A. S. Furaiji, “Applicability of solar systems with various technologies and sun-tracking: A case study of Baghdad, Iraq,” Future Energy, vol. 1, no. 2, pp. 3-8, Aug. 2022, doi: 10.55670/fpll.fuen.1.2.2.

[24] M. H. Ibrahim and M. A. Ibrahim, “The optimum PV panels slope angle for standalone system: Case study in Duhok, Iraq,” IOP Conf. Ser.: Mater. Sci. Eng., vol. 1076, no. 012004. 2021, doi: 10.1088/1757-899X/1076/1/012004.

[25] S. Fawaz, F. A. Ali, and T. K. Razaq, "Tilt angle optimization of solar collectors for maximum radiation in three Iraqi cities," International Journal of Engineering and Industries (IJEI), vol. 3, no. 4, pp. 99-107, Dec. 2012.

[26] F. A. Ali and S. Fawaz, “Evaluation of the best slope angle for a flat-plate solar collector,” Kirkuk Journal of Science, vol. 12, no. 4, pp. 157-178, Sept. 2017, doi: 10.32894/kujss.2017.132393.

[27] A. Z. Hafez, A. Soliman, K. A. El-Metwally, and I. M. Ismail, “Tilt and azimuth angles in solar energy applications–A review,” Renewable and Sustainable Energy Reviews, vol. 77, pp. 147-168, Sept. 2017, doi: 10.1016/j.rser.2017.03.131.

[28] M. Despotovic and V. Nedic, “Comparison of optimum tilt angles of solar collectors determined at yearly, seasonal, and monthly levels,” Energy Conversion and Management, vol. 97, pp. 121-13, June 2015, doi: 10.1016/j.enconman.2015.03.054.

[29] K. Bakirci, “Prediction of diffuse radiation in solar energy applications: Turkey case study and compare with satellite data,” Energy, vol. 237, no. 121527, Dec. 2021, doi: 10.1016/j.energy.2021.121527.

[30] S. Oliveira-Pinto and J. Stokkermans, “Assessment of the potential of different floating solar technologies– Overview and analysis of different case studies,” Energy Conversion and Management, Vol. 211, no.112747, May. 2020, doi: 10.1016/j.enconman.2020.112747.

[31] D. K. Lee, J. In, and S. Lee, “Standard deviation and standard error of the mean,” Korean Journal of Anesthesiology, vol. 68, no.3. pp. 220-223, May. 2015, doi: 10.4097/kjae.2015.68.3.220.

[32] Statista, “Electricity prices for enterprises worldwide in June 2023, by select country,” Accessed: Feb. 25, 2024. [Online]. Available: https://www.statista.com/

[33] R. Uddin and H. Duzkaya, “High-efficiency lead-free dual-absorber perovskite solar cells employing V_2O_5 and CdS transport layers: A SCAPS-1D study,” in Proc. 2025 13th International Conference on Smart Grid, Glasgow, U.K., 27-29 May 2025, pp. 594–598, doi: 10.1109/icSmartGrid66138.2025.11071720.