International Journal of Power Electronics and Drive System (IJPEDS)
Vol. 16, No. 3, September 2025, pp. 1914~1925
ISSN: 2088-8694, DOI: 10.11591/ijpeds.v16.i3.pp1914-1925 ❒ 1914

Investigation of optimal tilt, orientation, and tracking of a solar PV system in Iraq

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Article Info

Article history:

Received Dec 10, 2024
Revised Apr 21, 2025
Accepted May 25, 2025

Keywords:

Iraq solar
Optimal tilt
PV systems
PV tracking
Solar energy

ABSTRACT

This paper examines the effect of tilt angle and tracking modes on energy performance of a PV system under Iraqi weather conditions. A 5-kWdc rooftop residential PV system is modeled and simulated using system advisor model (SAM) to investigate its optimal configuration of tilt angle and tracking axes for maximum energy extraction. The system is simulated with meteorological datasets for all 18 Iraqi provinces. The effect of soiling losses due to dust accumulation on incident irradiance and energy generation is considered as most Iraqi territories suffer from frequent dust storms yearly. The system annual AC energy and optimal tilt angles are evaluated and compared in five different scenarios including fixed-axis with tilt at latitude, fixed-axis with tilt at annual optimal angle, fixed-axis with tilt at monthly annual angle, one-axis tracking and dual-axis tracking. The results showed that considerable amount of energy is left unharnessed in fixed-axis scenarios when tilt angles are adjusted at latitude and optimal annual values. Using optimal monthly tilt with fixed-axis improved energy extraction by 5-6% for all locations. Energy performance is further improved with one-axis tracking. Dual-axis tracking achieved highest energy yield compared to other scenarios. Overall, mid-south provinces provided highest energy opportunities among others.

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1. INTRODUCTION

The Iraqi power system has been suffering from daily power outages for more than three decades. Such power outages can reach up to twelve hours per day, and the situation gets worse as temperatures hit 50 °C during scorching summers. The reason behind this power shortage is attributed to different technical reasons including deterioration of the power network infrastructure, increasing demand, lack of power plants fuel as well as other political and financial challenges [1]. Currently, the total power generation in Iraq is around 28,000 MW, and this amount covers only about 60% of the country’s total demand which is estimated to be 40,000 MW [2]. Utilizing sustainable energy sources, especially solar energy, is one of the key tools that can be adopted to combat the electric power crisis in Iraq and bridge the gap between demand and supply. However, despite the abundant amount of solar energy that Iraq receives throughout the year, solar energy is underutilized and the government’s steps towards investing in solar energy projects remain limited [3]. One of the primary stumbling blocks that hinders wider adoption of solar energy in Iraq is related to financial limitations.

Installing photovoltaic (PV) systems, whether as grid-scale or distributed, is considered a capital-intensive project [4]. For instance, homeowners find it unaffordable and out of their reach to install rooftop PV systems. Therefore, the economic feasibility of solar energy systems is a crucial factor that influences the acceptance and promotion of solar systems. The economic value and return of a PV system are primarily reliant on the amount of power a PV system generates annually. Put differently, the more power the PV system provides, the more economically acceptable it will be. The amount of solar radiation a PV module can harvest and convert into electrical energy depends significantly on the location, orientation, and direction of the panel with reference to the sun's rays [5], [6]. Therefore, improper installation and orientation of PV subarrays can affect their performance and annual energy yield. Thus, to maximize power generation from a PV system, its subarray(s) orientation must be optimized to increase the surface area exposed to solar irradiance on a daily and seasonal basis [7]. According to the cosine effect [8], maximum irradiance harvest can be attained when the surface of a PV panel is oriented such that it makes a right angle with the direction of the incident sun rays. In other words, when the angle of incidence equals zero relative to the normal plane to the PV module surface, all incident rays will penetrate the PV glass layer. Otherwise, when the PV surface is not perpendicular to the path of irradiance rays, a proportion of the rays will be reflected away from the PV surface, affecting its efficiency.

The PV array surface orientation is defined in terms of two main parameters, i.e., angles that are the angle of tilt and the azimuth angle. These angles depend on the tracking axes of the subarray. There are three different configurations of PV subarray tracking, including fixed, azimuth, and two-axis tracking. More details about each tracking scheme are discussed in section 3. Optimal selection of the most effective combination of these orientation parameters and tracking methods, and their effect on PV system power yield has been a topic of interest of a large corpus of research over a wide range of geographical regions [9], [10]. Evaluation of optimal tilt angle that achieves maximum power generation by a PV system in three Iraqi governorates was discussed in [11]. Mathematical models were used to estimate power intensity extracted from solar radiation data in Baghdad, Diyala, and Tikrit, which are located on the same latitude that is between 33° and 34°. The results showed that the optimal annual angle for the three locations is 31°, as the three cities share the same latitude. The optimal monthly tilt angle is different for each city. However, the difference is very slight, and that is also attributed to the fact that the studied locations fall within the same latitude. The limitation of this study is that it did not cover a diverse range of geographical locations in Iraq. Besides, the simulated system operates in a fixed-tracking mode and does not consider the effect of the azimuth angle. A similar effort was made in [12] for a fixed-axes system in Duhok governorate, taking into account topography restrictions imposed by mountains. The optimal annual tilt angle was quantified to be 25° for Duhok. However, the monthly analysis of the optimal tilt angle was not discussed. This matter was investigated in [13], which analyzed the optimal annual and monthly tilt angle of a simulated PV system located in Duhok. Compared to [12], the optimal annual tilt angle was evaluated to be 32.7° while the optimal monthly tilt angle ranged from 1.5° to 64° depending on the months of the year. However, the analysis did not take into account the azimuth tracking effect. The optimum tilt of Duhok was also evaluated in [14] and provided different optimal annual and monthly tilt angles compared to [13]. The optimal annual tilt angle was 36.88°, which is higher than the value obtained in [13]. Noticeable differences were also observed in the optimal monthly tilts in all months, but the variance was more significant in summer, particularly the months of May, June, July, and August. The optimal tilt of a solar system in Baghdad was discussed in [15] and [16] for a fixed-angle system, and in [17] for a one-axis tracking system, and in [18] for a two-axis tracking system. Duhis *et al.* [19] discussed the effect of albedo on the amount of incident radiation and power generated by a 690 W, off-grid PV system installed in Karbala. The correlation between albedo value and optimal tilt angle was studied by evaluating and comparing the gain in system energy yield at different settings of albedo value and tilt orientations. However, a monthly analysis was not provided. Insights on the optimal tilt angles of PV panels in four different Iraqi cities were offered in [20]. The results confirmed that adjusting the annual tilt angle to be equal to the location latitude can be a feasible choice to extract maximum power by a PV system. Abdullah and Abdulkarim [21] shed light on the feasibility of a simulated home PV system in Erbil that utilized a tracking mechanism and compared the system energy performance under one-axis and two-axis modes.

The investigations presented in the aforementioned literature were each limited to certain locations and cities, and they did not look at all governorates at the same time, which makes it hard to gain comparative insights between solar potential of different Iraqi locations. Besides, the reviewed works did not consider different orientation tracking schemes, including one-axis and two-axis tracking together with optimal tilt analysis. The former shortcoming was addressed in [22], which studied the effect of optimal tilt angle on energy performance of PV panels in 15 Iraqi governorates, excluding Kurdistan region governorates. However, tracking axes were not included in the study. From the literature review above, it can be said that different approaches were used to evaluate optimal orientation conditions of PV systems to maximize their energy production. These approaches were either based on numerical evaluation of mathematical models or on using various solar simulation tools. Therefore, it is challenging to make consistent decisions about the precise optimal tilt orientation for a certain location based on the scrutinized contributions because the results are discrepant and disagree to some extent. This discrepancy is also attributed to the use of different weather datasets from different resources. The other shortcoming that has been identified in the reviewed literature is that irradiance losses due to the soiling effect were not considered in the analysis, which can lead to an inaccurate evaluation of PV system performance.

The aim of this work is to overcome these challenges by providing a countrywide, complete analysis of optimal tilt angle and orientation of a PV system in Iraq. Monthly, seasonal, and yearly values of optimal tilt angle with one-axis and two-axis tracking are investigated using the System Advisor Model (SAM) from the National Renewable Energy Laboratory (NREL) [23] which provides a solar performance model based on solar and meteorological datasets from the National Solar Radiation Database (NSRDB) and other sources, taking into consideration system losses, including irradiance and electrical losses. The remaining part of this manuscript is structured as follows: i) In section 2, the mathematical relationships between the components of solar irradiance are presented based on geometric analysis in the case of sloped surfaces; ii) Section 3 discusses the research methodology including the design of the PV system and the simulation environment; iii) The results are discussed in section 4 in five scenarios; and iv) Section 5 is dedicated for the conclusions and thoughts about further research based on this work.

2. THE COMPREHENSIVE THEORETICAL BASIS

2.1. Mathematical description of solar radiation and optimal tilt

Tilt angle and azimuth orientation play a crucial role in maximizing PV panel exposure to solar radiation and, consequently, maximizing energy generation [24]. To evaluate the optimum values and settings of these angles in any PV system, it is important first to understand the behavior and mechanisms of solar radiation that is received by a horizontal plane mounted on Earth's surface. Before striking Earth, solar radiation rays travel through the atmosphere, and part of that solar radiation is lost due to absorption by the particles and molecules that fill the atmosphere. Another part of solar radiation scatters due to the same effect; however, it still reaches the surface of the Earth. Therefore, depending on this behavior, there are two different definitions (components) of solar irradiance that fall on a horizontal surface stationed on Earth. The component of solar irradiance that falls on a flat surface in a normal direction is defined as the direct normal irradiance (DNI). It represents the quantity of solar flux per square meter that is collected by a surface vertical to the direction of the sun through a narrow solid angle. The DNI component constitutes the highest amount of irradiance reaching the surface, especially on clear days. DNI is crucial for solar energy systems that depend on concentrated solar irradiance. The other component of solar irradiance that is scattered or diffused throughout the ambient by objects such as clouds is defined as the diffuse horizontal irradiance (DHI). It is the amount of solar irradiance that is received by a horizontal surface per unit area from sun rays that are not directly coming from the sun [24]. The sum of these two components is defined as the global horizontal irradiance (GHI), which constitutes the total solar irradiance received by a horizontal plane with respect to the ground level. Mathematically, GHI, DNI, and DHI can be related as (1) [25].

$$H_G = H_F + H_D \cos\theta \tag{1}$$

Where H_G, H_D and H_F are the GHI, DNI, and DHI components, respectively. θ is the zenith angle which represents the angle that DNI rays make with the vertical direction. Figure 1 shows a diagram that provides further description of GHI components.

For a tilted surface sloped at an angle β with respect to the ground level, it is required to evaluate the total amount of radiation the tilted surface receives in terms of global radiation of a horizontal surface, taking into account the inclination effect on the direct and diffuse components. The behavior of the diffuse radiation component mainly depends on the sky dome conditions in terms of cloudiness, reflectivity of the surroundings, and other environmental conditions. Therefore, the total daily solar radiation on a sloped surface, H_T is given in (2) [26], [27].

$$H_T = H_{TD} + H_{TF} + H_{TR} \tag{2}$$

Where H_{TD} is the daily direct radiation component received by the tilted surface in (W/m^2), H_{TF} is the diffuse radiation component on the tilted surface in (W/m^2), and H_{TR} is the radiation component reflected off the ground and received by the surface in (W/m^2).

The daily direct radiation component, H_{TD} in (2) can be evaluated in terms of the monthly average of the daily global, H_G and diffuse, H_F radiation components received by a horizontal surface as (3) [26], [27].

$$H_{TD} = (H_G - H_F) \times R \tag{3}$$

Where R is the ratio of the average per-day direct radiation on a tilted surface to that on a horizontal surface over a period of a month.

The value of R depends on the hemispheric location of the surface tilted towards the equator. For a system located in the northern hemisphere (in the case of Iraq), R can be expressed as (4).

$$R = \frac{\cos(\emptyset-\beta)\cos\delta\sin w_s + (\pi/180)w_s\sin(\emptyset-\beta)\sin w_s}{\cos\emptyset\cos\delta\sin w_s + (\pi/180)w_s\sin\emptyset\sin\delta} \quad (4)$$

Where $\emptyset$ is the latitude; β is the tilt angle of the surface with respect to the horizontal level; δ is the sun angular location in the sky at the moment when it is at its highest elevation; and w_s is the azimuth angle at astronomical sunset with respect to the tilted surface. The daily ground-reflected radiation component can be expressed as (5).

$$H_{TR} = \rho H_G \times \frac{(1-\cos\beta)}{2} \quad (5)$$

Where ρ is ground reflectivity.

Unlike, H_{TD} and H_{TR} which obviously can be measured without difficulties, as can be seen in (3) and (5), H_{TF} is strongly affected by its distribution throughout the sky dome, and measuring it is not a straightforward process. There are two models used to evaluate the diffuse component: the isotropic model and the anisotropic model. The chief difference between the two models lies in the way they incorporate the sky effect on the diffuse radiation component. In the isotropic model, which is the focus of this work, an approximation is made by assuming that the sky diffuse component is uniformly distributed throughout the sky dome [26]. Therefore, according to an isotropic model, the daily diffuse component can be calculated as (6).

$$H_{TF} = H_F \times \frac{(1+\cos\beta)}{2} \quad (6)$$

Thus, the total daily solar irradiance on a tilted surface is expressed as (7).

$$H_T = (H_G - H_F) \times R + H_F \times \frac{(1+\cos\beta)}{2} + \rho H_G \times \frac{(1-\cos\beta)}{2} \quad (7)$$

It is clear that the total amount of solar radiation a tilted surface receives per day strongly depends on the tilt angle, β in a nonlinear relationship. Hence, the optimal value of β can be selected as the value at which H_T is maximized at certain values of the other parameters in (7).

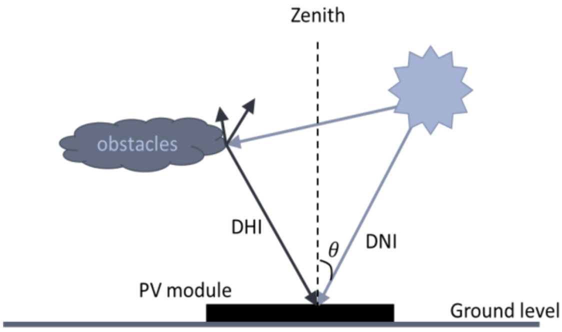

Figure 1. Radiation components received by a surface horizontal to ground level

2.2. PV panel angles and sun tracking

The orientation of a PV panel surface is selected in terms of two angles that are the tilt angle, which was described in detail in the previous section, and the azimuth angle which is basically the panel's surface alignment with the sun position along the north-to-south direction [28]. According to the configuration of the PV panels mounting structure, there are four modes of PV tracking that are the fixed mode, azimuth tracking, one-axis tracking and the two-axis tracking modes [23], [29]. In the first mode, the panels are stationary and installed at a fixed tilt and azimuth angle, $\beta = \beta_o$.

In one-axis mode, the panels are adjusted at a fixed azimuth angle, $\gamma = \gamma_o$ and tilt angle, $\beta = \beta_o$ but they rotate along the tilted axis from east to west throughout the day time. In azimuth tracking, the panels track the sun azimuth angle throughout the day while adjusted at a fixed tilt angle, $\gamma = \gamma(t)$, $\beta = \beta_o$. In two-axis tracking, the modules' tilt and azimuth angles are adjusted to follow sun position on seasonal and daily basis. Therefore, the tilt and azimuth angles become time related and are expressed as $\beta = \beta(t), \gamma = \gamma(t)$, respectively.

3. METHODOLOGY

A 5 kWdc rooftop PV system was designed and modeled in system advisor model (SAM) for optimal tilt and orientation simulations with weather data for all Iraqi provinces. The PV array was designed with one string which consists of 10 (500 Wdc, 42 Vdc, Monocrystalline silicon) modules in series. One PV inverter with capacity of 4.37 kWdc, 4.2 kWac was used to achieve a DC to AC ratio of 1.19.

All of the system AC power generated is supposed to be delivered to the AC line, i.e., no power curtailment limit is used. The PV system does not include any battery energy storage as the main purpose of the simulated system is to evaluate its energy performance with respect to different tilt and orientation settings. Shading effect is not considered as the system is assumed to be installed on a clear rooftop without shading objects. However, irradiance losses caused by soiling is considered and incorporated in the system analysis because it is one of the main contributions of this work. Soiling is defined as the effect of particles accumulation such as dust, bird dung and other flying debris on the surface of PV panels causing reduction in the amount of solar irradiance received by the panels [30]. Consequently, the electric power generated by the PV system will be greatly affected resulting reduced system efficiency economic feasibility. In fact, soiling effect becomes a serious issue in arid and desert areas where airborne dust is thick and sand and dust storms are more frequent. Besides, in desert areas that are near the equator, PV panels are typically oriented at low tilt angles and that makes the panels more prone to dust accumulation. In fact, soiling effect is not limited to desert and dry areas only, it can also affect PV systems installed in cities and farms due to accumulation of fuel emissions and agricultural debris [30]. Therefore, for PV systems installed in Iraq, in which desert constitutes about 30% of its territory, PV soiling must be taken into account when studying the performance and feasibility of any PV system. Soiling losses range from 3% to 40% of the system annual power production depending on the location and its dust storm profiles as well as whether periodic cleaning is being provided to the PV system or not. According to reported experimental data about soiling effect on power production of PV systems in Iraq and neighboring countries [31], the monthly soiling losses of the designed system due to dust accumulation over a period of one year is selected to be increments of 2.5% each month which is equivalent to an average annual soiling losses of 16.25% with maximum of 30% in December given that the system is not cleaned over the one-year analysis period. The total area of modules in the array is 24 m^2 which requires ground area of about 75 m^2. A block diagram of the studied PV system is shown in Figure 2.

After the system was designed in SAM, weather data for each of the studied locations (18 Iraqi provinces) were added, and different sets of simulations were conducted to investigate the system's power and energy performance under different operational conditions in terms of orientation and tracking modes. Accordingly, different scenarios were considered. The simulation results of each scenario are explained and discussed in the next section. It is important to mention here that the azimuth angle is set to 180^o as the system is oriented facing south which is the typical direction for PV system installed in a location in the northern hemisphere.

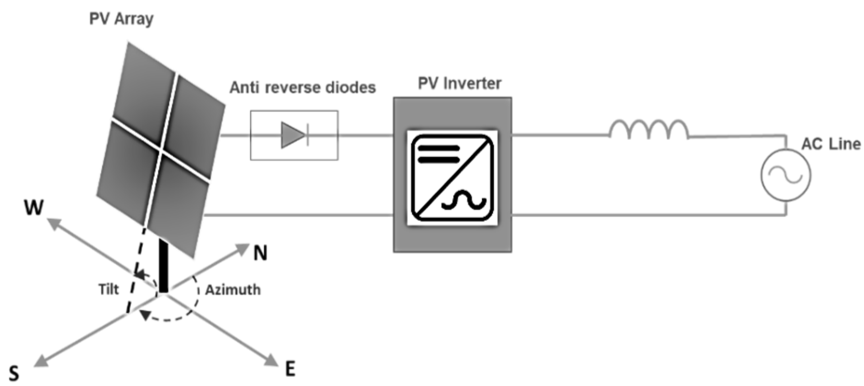

Figure 2. A block diagram of the studied PV system

4. RESULTS AND DISCUSSIONS

Information of the studied 18 locations including their geographical coordinates, average temperature, and irradiance components are listed in Table 1. It is obvious from the table that the highest average daily GHI irradiance can be obtained in Basra while Duhok receives the lowest daily irradiance. It can also be seen that Middle Euphrates and western provinces receive a plenty amount of irradiance throughout the year. For more details about the solar irradiance of the considered locations, Figure 3 shows the average hourly distribution of GHI irradiance for all provinces as calculated by the SAM model based on the provided weather data of the locations. Figure 3 shows that all locations receive 8 hours of average irradiance of 550 – 650 W/m^2. Now, with the given solar irradiance data, the PV system is simulated under different scenarios. In the following sections, the results of each scenario are presented and discussed.

Table 1. Geographical and irradiance information of the studied locations (typical meteorological year (TMY) 2007-2021)

Province	Latitude (o)	Longitude (o)	Elevation (m)	Average temp. (C)	GHI (kWh/m^2/day)	DNI (kWh/m^2/day)	DHI (kWh/m^2/day)
Al-Anbar	33.45	43.31	48	24.6	5.66	6.63	1.42
Babil	32.45	44.45	27	25.3	5.63	6.57	1.38
Baghdad	33.26	44.23	34.7	24.9	5.61	6.64	1.36
Basra	30.51	47.78	2.6	27.1	5.81	6.67	1.43
Dhi Qar	31.01	46.23	1.45	27.1	5.74	6.52	1.45
Al-Qādisiyyah	31.95	44.95	20	26.3	5.69	6.6	1.41
Diyala	34.35	45.38	202	24.2	5.5	6.48	1.38
Duhok	36.86	43	276	18.8	5.17	6.24	1.3
Erbil	36.23	43.96	408.7	21.3	5.3	6.34	1.33
Karbala	32.56	44.05	29	25.6	5.73	6.75	1.39
Kirkuk	35.46	44.34	323.4	23.6	5.45	6.5	1.37
Maysan	31.85	47.16	9	26.9	5.65	6.45	1.44
Muthanna	31.26	45.26	6	26.5	5.77	6.63	1.44
Najaf	31.95	44.31	32	25.9	5.78	6.76	1.41
Ninawa	36.3	43.14	216.1	22.1	5.31	6.33	1.36
Salah Al-Din	34.57	43.67	107	24.4	5.58	6.59	1.4
Sulaymaniyah	35.55	45.45	853	18.5	5.35	6.35	1.37
Wasit	32.5	45.81	19	25.9	5.65	6.58	1.41

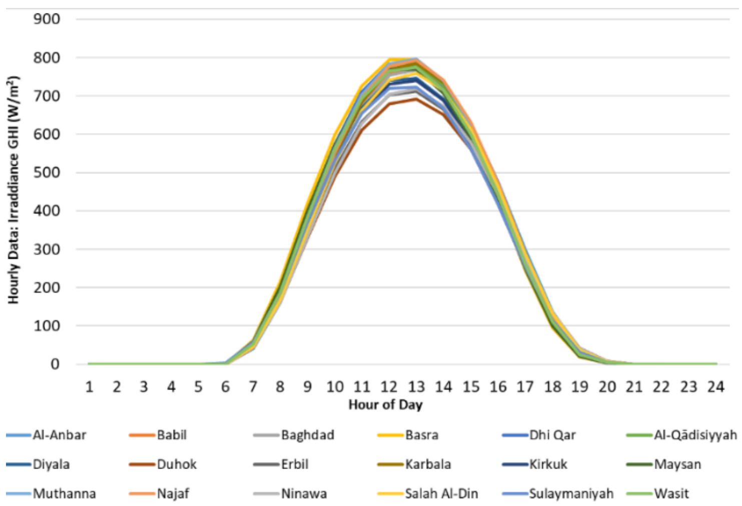

Figure 3. GHI irradiance of the 18 Iraqi provinces according to typical meteorological year (TMY) 2007-2021 dataset of Iraqi region downloaded from NSRDB

4.1. Scenario 1: fixed-axis, tilt = latitude

In this scenario, the system is simulated with a fixed tilt angle. As a common practice, the value of tilt angle is adjusted to the location latitude for the best performance of a PV system. However, this configuration does not necessarily achieve maximum power extraction from a PV system at all locations and times. Thus, it is significant to investigate the effectiveness of such a tilt angle in all of the studied locations and then compare the results to the optimal tilt angle scenario. The system performance in each scenario is assessed in term of five energy parameters including the plane of the array (POA) irradiance which is one of the essential indicators of PV system performance. It is a measure of how much incident irradiance the front side of PV panels receive over time. Annual total POA results in kWh were obtained with and without the effect of soiling losses. The other three parameters are the annual nominal DC energy produced by the system, the annual gross DC energy generated and the annual AC energy delivered to the load. The results of this scenario are listed in Table 2 for the

18 locations. The annual DC and AC energy are evaluated based on the POA irradiance after including soiling losses. The tilt angle is fixed throughout the year at the location latitude presented in Table 1. First the overall results are compared for all locations. The effect of soiling loss can be noticed by comparing the values of total POA irradiance before and after soiling effect, which is selected to be 16.25% as an annual average. It can also be observed that only 21% of the total irradiance received by the panels is converted into DC energy, which can be interpreted as the effect of the PV panels inefficiencies, for the efficiency of the selected PV panels is 21%. By comparing the nominal and gross DC energy values as well as the AC energy values, one can relate to the effect of DC losses due to DC wiring, diodes, and DC power optimizer on one hand, and the AC losses caused by the inverter inefficiency and AC wires on the other hand.

Now, by looking at the results of each location, it is clear that Najaf had the highest annual AC energy which amounted to 8626.8 kWh followed by Karbala with annual AC energy of 8597.86 kWh. Muthanna and Basra had nearly equal annual AC energy production and both came as the third highest. According to Table 1, these four provinces have the highest GHI and DNI values that both have significant effect in the amount of electric energy generated by the PV system. It can also be inferred from this scenario that a PV system installed in Duhok will produce the lowest amount of energy compared to the other studied locations. In general, northern provinces had the least amount of generated energy compared to mid and southern provinces. These disparities in the system performance can also be attributed to variations in the DHI received by the modules per unit area from one location to another. The DHI component of solar radiation is the amount of radiation that reaches the modules from the sun indirectly after being reflected by clouds and particles in the atmosphere. However, this scenario does not provide a clear picture about selecting the optimal tilt. The next scenarios attempt to identify the best tilt that achieves maximum energy extraction.

4.2. Scenario 2: fixed-axis, tilt = optimal annual value

In this scenario, instead of setting the panels tilt to the location's latitude, the tilt angle was optimized for each location based on the highest annual AC energy generated by the system. For each province, a set of simulations of the PV system were conducted in SAM for a range of input tilt angles and compute the annual AC energy at each input tilt. The optimal tilt angle is selected as the value at which the annual AC energy is maximized. Figure 4 shows a sample of the optimal tilt identification curve for Karbala location which indicates that optimal tilt is 31°. Table 3 lists the optimal annual tilt angle for each location compared to the location's latitude.

It can be noticed that the value of optimal annual tilt is close to latitude angle for most of the location with a slight deviation. The deviation of optimal tilt from latitude is less than 2° for most of the locations. However, optimal tilt in northern and mid-northern provinces deviated from latitude for more than two degrees, as highlighted in Table 3. In other words, moving towards the south, the annual optimal tilt moves closer to latitude. Setting the tilt angle to the optimal annual value obtained in Table 3 resulted in minor increase in the annual energy compared to scenario 1. Yet, setting a fixed tilt angle over the whole year does not allow users to make the most of the PV system, and a considerable amount of PV energy will remain untapped. Therefore, adjusting the tilt angle on monthly basis can extract more energy from the system. This technique is investigated in the next scenario.

Table 2. Model results of scenario 1: fixed-axis with tilt = latitude

Province	Total POA irradiance (kWh/yr)	Total POA irradiance after soiling (kWh/yr)	Annual nominal DC energy (kWh/yr)	Annual gross DC energy (kWh/yr)	Annual AC Energy (kWh)
Al-Anbar	54,568	45,794.8	9,656.72	9,154.64	8,495.89
Babil	54,054.3	45,368.2	9,568.19	9,043.68	8,393.11
Baghdad	54,211.1	45,435.3	9,582.21	9,087.79	8,430.4
Basra	55,238.9	46,333.3	9,774.41	9,238.09	8,567.4
Dhi Qar	54,594	45,844.5	9,668.94	9,087.51	8,433.35
Al-Qādisiyyah	54,574.5	45,804	9,660.48	9,086.89	8,432.31
Diyala	53,309.3	44,681.3	9,420.74	8,868.13	8,227.53
Duhok	50,615.2	42,327.4	8,922.13	8,504.01	7,890.63
Erbil	51,693.3	43,318.9	9,131.09	8,664.19	8,039.15
Karbala	55,242.1	46,401.7	9,787.38	9,270.01	8,597.86
Kirkuk	53,350.9	44,643	9,412.59	8,859.72	8,221.83
Maysan	53,849.8	45,160.1	9,523.42	8,939.06	8,293.44
Muthanna	55,148.3	46,294.3	9,764.14	9,258.48	8,587.78
Najaf	55,511.6	46,601.5	9,829.34	9,300.27	8,626.79
Ninawa	51,894.8	43,431.1	9,155.09	8,641.49	8,020.4
Salah Al-Din	54,151.8	45,434.9	9,580.51	9,077.48	8,419.95
Sulaymaniyah	52,315.1	43,745.8	9,222.36	8,815.08	8,168.25
Wasit	54,431.2	45,669.6	9,632.02	9,118.83	8,458

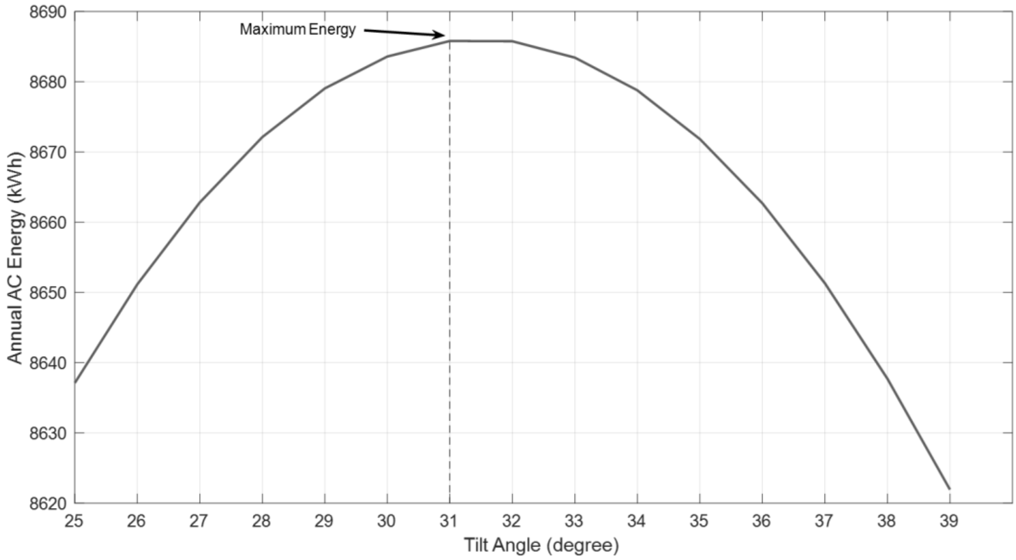

Figure 4. Annual AC energy vs. annual tilt showing optimal value for Karbala

Table 3. Optimal annual tilt angle for the 18 locations according to scenario 2

Location	Latitude	Optimal annual tilt	Deviation	Location	Latitude	Optimal annual tilt	Deviation
Al-Anbar	33.45	32	1.45	Karbala	32.567	31	1.567
Babil	32.45	31	1.45	Kirkuk	35.469	33	2.469
Baghdad	33.267	32	1.267	Maysan	31.85	30	1.85
Basra	30.517	30	0.517	Muthanna	31.267	30	1.267
Dhi Qar	31.017	30	1.017	Najaf	31.95	31	0.95
Qādisiyyah	31.95	31	0.95	Ninawa	36.306	33	3.306
Diyala	34.35	32	2.35	Salah Al-Din	34.5757	32	2.5757
Duhok	36.867	33	3.867	Sulaymaniyah	35.55	33	2.55
Erbil	36.233	33	3.233	Wasit	32.5	31	1.5

4.3. Scenario 3: fixed-axis, tilt = optimal monthly value

To identify the monthly optimal tilt angle, SAM model is simulated with a range of input tilt angles and the AC energy for each month is computed over the entire year. The tilt angle value that yields the maximum energy during a certain month represents the optimal tilt angle of the month. The same set of simulations was implemented for each location, and the results are shown in Figure 5. It is clear that the optimal tilt angle varied over a wide range during the year according to the sun seasonal tilt and that all locations followed the same trend within a narrow margin that did not exceed 6°. In winter months, high tilt is required for maximum energy extraction while in summer months, the panels need to be tilted at low angles to align with the sun seasonal track for maximum exposure to irradiance. After that, the system was simulated with tilt angle set to the optimal monthly values obtained in the previous step. The annual AC energy was then calculated for each location. The locations demonstrated the same trend in terms of energy yield where Najaf had the highest value and Duhok had the lowest. Generally, compared to scenario 2 where the tilt angle was fixed at one value throughout the year, AC energy was increased by 5-6% for all the locations due to increase in irradiance exposure by PV panels when tilt angle tracks the monthly seasonal path of the sun.

4.4. Scenario 4: one-axis tracking

In this configuration, the PV panels are adjusted at a fixed azimuth, which is selected to be 180° for Iraq regions, and allow the panels to track the 24-hour sun position within a rotation angle set by “the tracker rotation limit” parameter in SAM model. Practically, the rotation angle limit depends on the tracking mechanism and the design of the tracker structure. Some tracking racks provide 60° rotation range and others are limited to 45°. In this scenario, the effect of the tracker rotation limit on the energy performance of the PV system was first investigated for a certain location as shown in Figure 6. It is obvious that the wider the rotation angle is the more solar energy the PV system can harness. However, for practical constraints related to tilt tracking systems available in the market, the angle of rotation was set to be 60° as a reasonable limit in this scenario. The annual AC energy was evaluated for each province and compared to the previous scenario, the energy increase achieved in the one-axis mode was between 16%-18% for all the locations. This increase is self-explanatory as the PV panels are allowed to track the sun daily east-west location maximizing the incident irradiance.

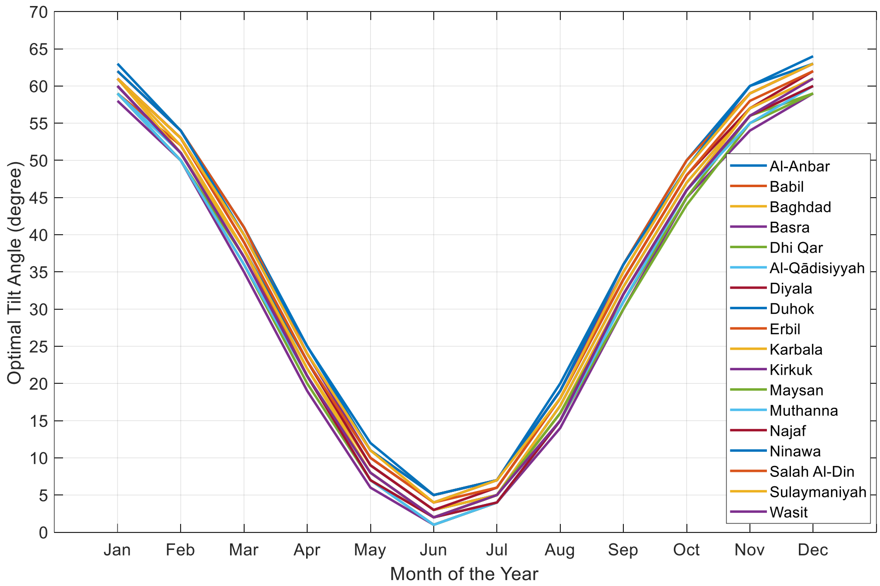

Figure 5. Monthly optimal tilt angle for 18 provinces

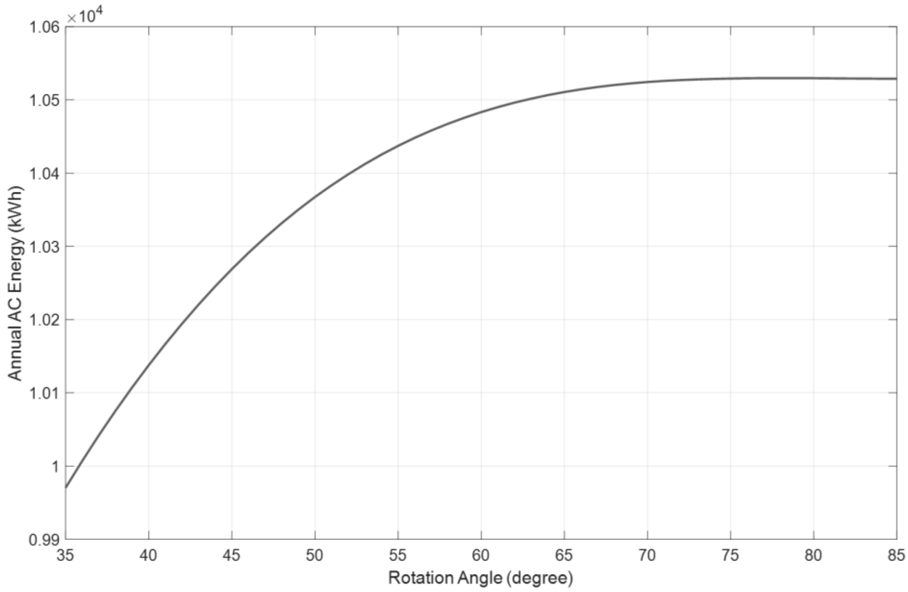

Figure 6. The relationship between one-axis rotation angle and energy yield for Karbala

4.5. Scenario 5: two-axis tracking

With two-axis tracking, the PV panels mount is automated to rotate along their vertical, azimuth, axis to track the sun seasonal location from north to south over the year, and to rotate along the tilt, horizontal, axis to track the sun daily location from sunrise to sunset in a mechanism similar to one-axis tracking. With this tracking mode, the PV panels are able to collect as much solar irradiance as available to the panels. This irradiance maximization was confirmed in the results which showed that the yearly energy of the system increased by 11-13% compared to previous scenario, i.e., the one-axis tracking. A detailed comparison of the energy performance of the system under scenarios 1-4 for all provinces is explained in Figure 7. It is clear that enabling tracking mode results in considerable enhancement of the system energy generation. Consequently, the system economic feasibility can also be enhanced. However, the additional cost incurred by installing tracking mounts should be considered which is a topic out of the scope of this work.

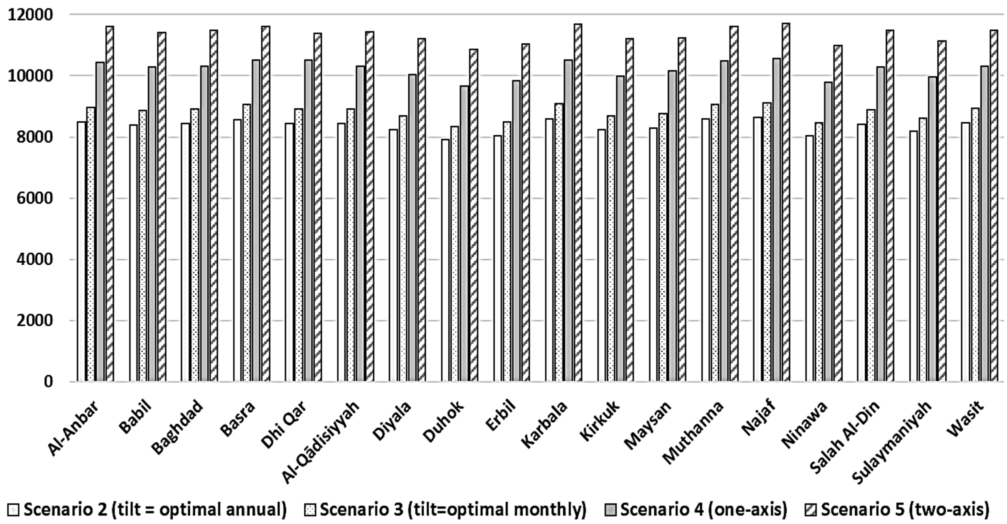

Figure 7. A comparison of system annual AC energy for all locations in four different scenarios

5. CONCLUSION

This paper delved into the evaluation of optimal tilt angle and tracking of a simulated solar PV system in 18 provinces in Iraq. The investigation was conducted through a SAM model to study the energy performance of a 5 kWdc PV system that was designed and simulated based on Iraqi weather conditions including the effect of soiling losses ascribed to dust deposition on panels. The optimal tilt angle was computed by running sets of simulations at a range of tilt angle inputs and evaluating the system energy performance as an output. It was observed that the common practice of setting the tilt angle to the location latitude did not achieve highest energy extraction for all of the studied locations and that led to underutilization of the system. Therefore, with this “golden rule” the system needs to be oversized to meet certain energy demand. Setting the tilt at annual optimal value resulted in a slight change for all locations because the optimal annual tilt was found to be 1°-2.5° above latitude. It was found that the system utilization and energy performance can be improved by setting a monthly tilt and that resulted in 5-6% increase in the yearly AC energy delivered to load by the system. The optimal monthly tilt varied from 1°-62° throughout the year based on the seasonal position of the sun. With one-axis tracking, the system annual energy increased by 16-18% for all the locations. The results also affirmed that further utilization can be achieved by using two-axis tracking with which annual energy increased by 29% compared to the optimal monthly tilt scenario. In all studied scenarios, soiling losses effect cannot be overlooked given that Iraqi weather is highly-polluted due to dust storms and pollution from daily life activities. Ignoring soiling losses in assessing PV system performance and their optimal orientation causes system under sizing because irradiance losses due to soiling can be as much as 40% in weather conditions like in Iraq especially when cleaning mechanisms are not applied. Overall, all Iraqi provinces have a significant untapped potential for solar energy generation with average annual GHI of 2 kWh/m^2. This work is concerned with the technical aspect of the design of a PV system in Iraq, but it still can be extended by considering the economic model of the system and the effect of additional cost of tracking system on the system economics.

FUNDING INFORMATION

The authors received no funding for this research.

AUTHOR CONTRIBUTIONS STATEMENT

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

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C : **C**onceptualization
M : **M**ethodology
So : **So**ftware
Va : **Va**lidation
Fo : **Fo**rmal analysis
I : **I**nvestigation
R : **R**esources
D : **D**ata Curation
O : Writing - **O**riginal Draft
E : Writing - Review & **E**diting
Vi : **Vi**sualization
Su : **Su**pervision
P : **P**roject administration
Fu : **Fu**nding acquisition

CONFLICT OF INTEREST STATEMENT

The authors have no conflict of interest to reveal.

DATA AVAILABILITY

The data that support the findings of this study are available on request from the corresponding author, [AZ].

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