Kurdistan Journal of Applied Research (KJAR)
Print-ISSN: 2411-7684 | Electronic-ISSN: 2411-7706

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Optimization of Tilt Angle of a PV System to Get Maximum Generated Power: a Case Study

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Article Info

Volume 5 - Issue 2 - December 2020

DOI:
10.24017/science.2020.2.7

Article history:

Received: 28 August 2020
Accepted:26 November 2020

Keywords:

Solar energy, solar radiation, monthly optimum tilt angle, yearly optimum tilt angle Duhok city, PVGIS.

ABSTRACT

The amount of solar irradiance falls onto photovoltaic (PV) panels depends highly on the tilt angle between the panels and the horizontal plane. Therefore, this angle must be chosen carefully so that the panels can absorb the largest possible amount of the solar beam. It is more convenient for the panels to be installed with the fixed tilt angle once a month or year as the cost and complexity of the solar tracking systems are high. This research determines monthly and yearly optimum tilt angles for 50 KWp solar system in Duhok city, Duhok Polytechnic University campus (Latitude/Longitude: 36.862, 42.980). Moreover, this work examines the performance of the system with different PV technologies which are Crystalline Silicon, Cadmium Telluride (CdTe), and Copper Indium Selenide (CIS) to determine which one is more convenient for Duhok weather. This work uses the PVGIS simulation tool, and the result shows that the 32.7 degree is the optimum tilt angle for fixed annually adjustment for the mentioned city. While the monthly optimum tilt angles were different for each month (the lowest tilt angle was 1.5° observed in June and the highest tilt angle was 63.9° recorded in December). Regarding PV technologies, the CdTe types generated more annual PV energy than other mentioned types, followed by CIS which produced more output PV energy than Crystalline Silicon.

1. INTRODUCTION

Currently, most countries around the world tend to use renewable energy to produce energy instead of using conventional power plants that are usually harmful to the environment and have a high cost. One of the most popular and effective renewable energy is solar energy that converts sunlight into electrical energy. Solar energy is free and environmentally friendly energy, and it is available everywhere. This energy is generated by solar PV panels which absorb the solar radiation and convert it to direct current. The greater the amount of absorbed solar radiation, the greater energy produced. The amount of solar radiation varies from a country to another according to their geographical location on the earth. The geographical location of Iraq is suitable for installing solar systems as it is located near to the equator which receives (6.5-7) kilowatt-hours per square meter. Further, the sunshine hours of Iraq are between 2800 to 3300 hours per year [1]. But unfortunately, Iraq in general and Kurdistan Region in particular, rely on traditional power sources to produce electricity such as oil and gas. However, their production is not enough for population requirements, and there is a shortage of electricity throughout the country. According to a statement from the Ministry of Electricity in the Kurdistan Regional Government, the Kurdistan region needs about 4200 MW to cover the people’s electricity demand. Whereas, according to that statement, the ministry can generate 3200-3300 MW of that power [2]. This is why the government should use renewable energies as alternative sources of power to conventional energy sources. Using renewable energy became so important especially after global warming hazards. Fortunately, community awareness has increased to protect the environment from pollution so they consider using renewable energy to fill the electricity shortage. Solar energy is considered an important source of renewable energy sources, which produces electricity from solar radiation. The generated energy from solar radiation is affected by many factors. One of the factors is an angle between PV panels and the horizontal plane which is called tilt angle. This tilt angle relies on the geographical latitude and climate of the selected location. For this reason, the optimal tilt angle should be chosen to maximize the absorbed amount of sun radiation by photovoltaic panels. Therefore, this manuscript presents the optimum tilt angle of a 50 KWp PV system in Duhok city.

The above paragraph gives a brief introduction to the specifications of Iraq weather and the situation of the electricity in the country. The next section presents a theoretical background of solar radiation and the angles that impact on its amount. Whereas section three reviewed some of the related papers that have been done in Iraq in general and in Duhok in particular. Section four shows the geographical location of Duhok city on the map where the proposed solar system to be installed and also produces the simulation program that was used in this research with a table of the descriptions. Then section five displays the obtained results of monthly and annually optimum tilt angles as well as the comparison between PV technologies. It also demonstrates an explanation of the obtained results.

2. SOLAR RADIATION

The earth receives a massive amount of solar radiation energy, an average of 1.7×10^{14} kW which is 10000 times more than the world's current energy demand. Hence the importance of studying and calculating the amount of direct and indirect hourly solar radiation, as it enters the process of converting solar energy into electricity through photovoltaic cells [3]. The amount of solar radiation reaching the earth’s surface cannot be controlled because it constantly changes and influences by several important factors. One of these factors is extraterrestrial solar radiation which is the average value of solar radiation reaching a per meter square in the outer atmosphere. This value depends on the space between the sun and earth. Yet this space is not constant since the orbit of the earth around the sun is elliptical. However, according to the World Meteorological Organization (WMO), this value is equal to 1367 W/m2 [4]. Other factors influence the rate of solar irradiance falling on the surface of the earth. These factors are solar angles which will be discussed in detail in the section below.

2.1. SOLAR ANGLES

Solar angles have a great role in influencing the amount of the solar beam reaching the earth (Fig. 1). One of the most effective angles, especially concerning solar energy panels, is the tilt angle (β) which is the angle between the PV panels and the horizontal plane, as shown in Fig. 2. It is oriented to the north for the southern part of the earth which is located below the equator line (Southern hemisphere). Whereas it is oriented to the south for the other part which is above the equator line (Northern hemisphere) [5].

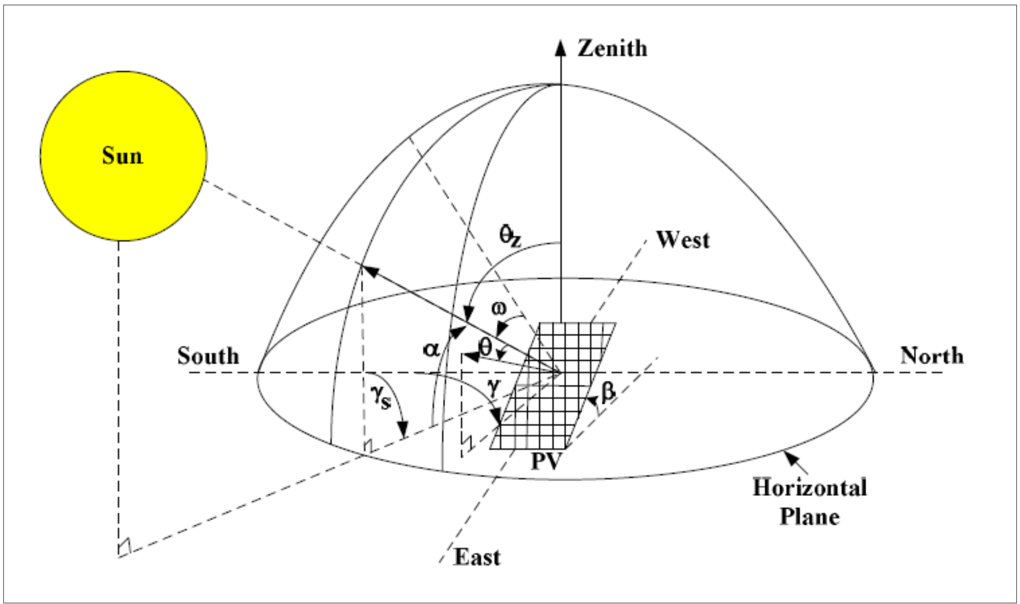

Figure 1: Solar basic angles

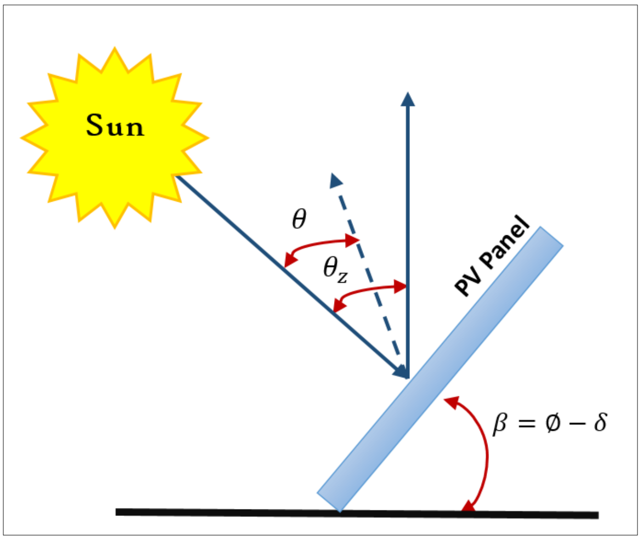

Figure 2: Tilt and Incidence angles

Equation (1) can be used to calculate the tilt angle when the plane is rotated around the west-east horizontal axis with daily adjustment [5].

$$\beta = |\phi - \delta| \qquad (1)$$

Where latitude angle (ϕ) is the angle between a particular point and the equator plane, and its value varies between $-90^{\circ} \leq \phi \leq +90^{\circ}$. While, δ is declination angle that lies between the solar radiation and equator plane as shown in Fig. 3, and its value varies between

$-23.45^{\circ} \le \delta \le +23.45^{\circ}$. It can be calculated using the following equation.

$$\delta = 23.45 \times \sin\left[360 \times \frac{(284 + d)}{365}\right] \qquad (2)$$

Where d is the day of a year and it starts from 1st of January (i.e. $d = 1$) [6][7][8][9].

Whereas, equation (3) is used to calculate the tilt angle if the plane is rotated around the west-east horizontal axis with continuous adjustment.

$$\tan\beta = \tan\theta_z \cdot \left|\cos\gamma_s\right| \qquad (3)$$

Where θ_z is zenith angle which lies between the vertical axis and the beam radiation, as shown in Fig. 2. It can be calculated using the following equation [10]:

$$\cos\theta_z = \cos\phi \cdot \cos\delta \cdot \cos\omega + \sin\phi \cdot \sin\delta \qquad (4)$$

Where (γ_s) is solar azimuth angle which is the angle between direct beam radiation and the south or north position of the sun.

$$\gamma_s = \cos^{-1}\left[\frac{\sin\alpha \cdot \sin\phi - \sin\delta}{\cos\alpha \cdot \cos\phi}\right] \qquad (5)$$

Where (α) is solar elevation angle which is between the horizontal plane and the beam radiation, so it can be calculated as follows:

$$\alpha = 90 - \theta_z \qquad (6)$$

Hour angle (ω) is one of the most important solar angles used in calculating solar radiation, and it is defined as the angle that the earth must be revolved to become the point studied just under the sun; which is the angle measured at the level of the equator between the longitude of the sun's light and longitude of the location. This hour angle is measured in hours and calculated by the following equation:

$$\omega = 15 \times (t_s - 12) \qquad (7)$$

Where t_s is solar time (hours) [11].

From Fig. 2, the incidence angle (θ) is the angle between sun radiation to a surface and the normal of that surface. It is calculated depending on other angles as follows [5][7]:

$$\theta = \cos^{-1}\left[\cos\phi \cdot \cos\omega \cdot \cos\delta + \sin\phi \cdot \sin\delta\right] \qquad (8)$$

While if the plane is rotated around the north-south horizontal axis with continuous adjustment, equation (9) is used to calculate the tilt angle.

$$\tan \beta = \tan \theta_z \cdot \left| \cos(\gamma - \gamma_s) \right| \qquad (9)$$

Where (γ) is the azimuth angle which is the angle between the south direction and the horizontal projection of direct sun radiation, as shown in Fig. 1. This angle varies between -180° and +180°, it is equal to 0° in the south, positive in the west, and negative in the east.

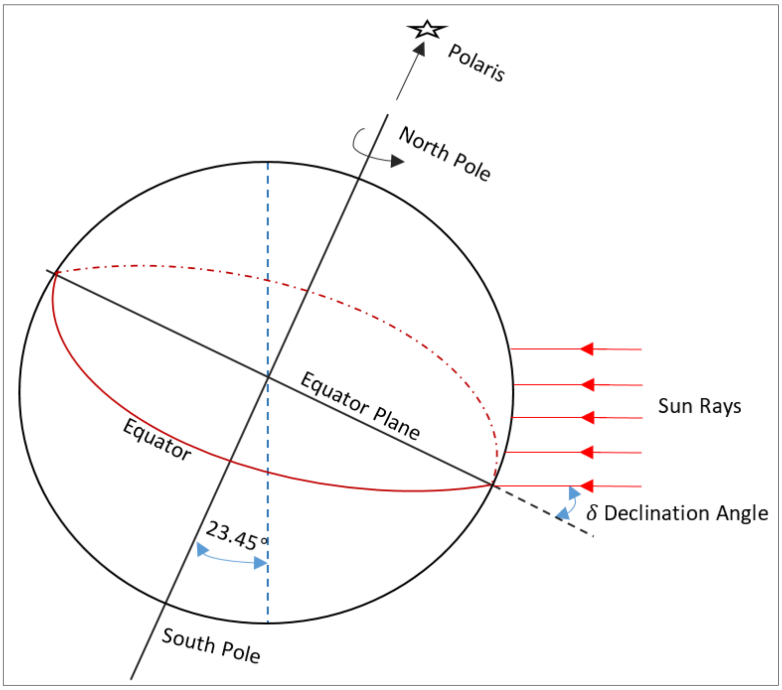

Figure 3: Declination angle

3. LITERATURE REVIEW

Many researchers have focused on the effect of the tilt angle on the amount of produced energy from the sun. The optimum tilt angle of PV projects cannot be compared with each other too easily because the output energy of PV panels highly relies on the geographical location. However, this paper reviews some of them, especially those conducted in the Duhok city or locations near Duhok city geographically. Starting from reference [12] that used a program on NASA website to find optimum tilt angles of all Iraqi provinces, and the results showed that the Duhok province has the highest tilt angle which is 34.5°. Dissimilarly, the proposed work in our paper determined that the 32.7° is a more appropriate yearly tilt angle for a PV system in Duhok city, which is distinctly different from that given in [12]. While reference [13] chose a tilt angle of 32.33° as the optimum angle for the same city (Duhok), which is slightly different from our result (32.7°).

Additionally, another work was done in [14] to determine the best tilt angles of the northern Iraqi cities (including Duhok city) using the Engineering Equation Solver (EES) program, it chose a tilt angle of 34° as the optimum angle of Duhok city. Reference [15] used a simulation tool for a solar system in southern Iraqi cities. It mentioned that the Iraqi southern cities had the same angle of 50° as the optimal tilt angle. On the contrary, reference [16] used a mathematical model programmed by EES in order to determine the optimum tilt angle of some southern Iraqi cities which

were Basrah, Amarah, and Nasiriyah; the result presented that the mentioned cities had different optimum tilt angles which were 28°, 30°, and 29° respectively.
Ref. [17] examined the optimum tilt angle of three Iraqi provinces which were Baghdad (latitude 33°20′), Tikrit (34°35′) and Diyala (33°14′), and the result showed that the mentioned locations had the same optimum tilt angle which was 31°. Ref. [18] proposed an algorithm to optimize the tilt angle based on MATLAB software for three different cities, one of them was Najaf which is located in the south of Iraq. Its result showed that the optimum tilt angle was approximately equal to the location's latitude where the PV panels to be installed. Similarly, the yearly tilt angle in [19] was near to the latitude of the selected location, which was the city of Khatkar Kalan (31.06°).

4. METHODS AND MATERIALS

The purpose of this work is to find the optimum tilt angle of 50 KWp solar system to be installed in Duhok Polytechnic University campus which in turn located in the center of Duhok city (Latitude/Longitude: 36.862, 42.980) in order to raise the rate of absorbed solar beam. Duhok city is one of the Kurdistan region's cities which is located in the northwest of Iraq, as shown in Fig. 4. In this research, the PVGIS simulation tool was used for 50 KWp fixed mounting, free-standing, Crystalline Silicon PV system; considering 14% system loss as given in Table 1. The value of the tilt angle was changed from 0 to 90 degrees (with increments of 1 degree) to examine the system performance with various tilt angles. The photovoltaic panels were oriented to the south as the chosen position located in the northern hemisphere. The results were observed for each tilt angle and compared to each other to determine the optimum degree, as given in the next section. The optimum tilt angle for the selected location in Duhok was determined then as an extra step the performance of the system was examined with three different PV technologies which are CdTe, CIS, and Crystalline Silicon.

Figure 4: Geographical location of Duhok city

Table 1: Description of the system

Latitude/Longitude	36.862, 42.980
PV installed power	50 KWp
PV technology	Crystalline silicon
Mounting system	Fixed mounting, free standing
System loss	14%

5. RESULTS AND DISCUSSION

5.1. MONTHLY OPTIMUM TILT ANGLE

As it has been mentioned earlier that the PVGIS simulation is used to investigate 50 KWp PV system performance in the Duhok city with different tilt angles for the sake of determining monthly optimum tilt angles, as shown in Fig. 5. The figure shows the monthly collected PV energy with different tilt angles. While Table 2 gives the monthly radiation and energy output of the PV system which were recorded for each tilt angle to determine the monthly optimum tilt angles. It is obvious from the results that the lowest optimum tilt angle appeared in June which was 1.5° while the highest optimum tilted angle was 63.3° in December. In the summer season, which includes May, June, July, and August months concerning Iraqi weather, the PV panels gave more energy with low tilt angles. While during the winter season (i.e. November, December, and February), more energy was acquired with high tilt angles. The PV panels generate more energy in summer due to the fact that the declination angle is high which in turn shorts the path of the sun-ray. Correspondingly, the panels' tilt angle can also be changed seasonally if the average value of optimum tilt angles of the four seasons is used to increase the absorption of solar radiation.

Table 2: PV panels' optimum tilt angle for each month of the year

Month	Optimum tilt angle (Degree)	Monthly radiation kW/m^2	Monthly energy output kWh
January	60.8	122.75	5052.38
February	52.1	130.3	5253.24
March	39	169.89	6612.7
April	23.6	184.89	6960.9
May	9.4	222.11	8159.91
June	1.5	249.35	8711.55
July	5	255.7	8733.4
August	18.5	239.57	8402.44
September	35.3	218.99	7918.76
October	49.3	181.11	6802.87
November	59.4	152.37	6080.84
December	63.6	134.22	6463.84

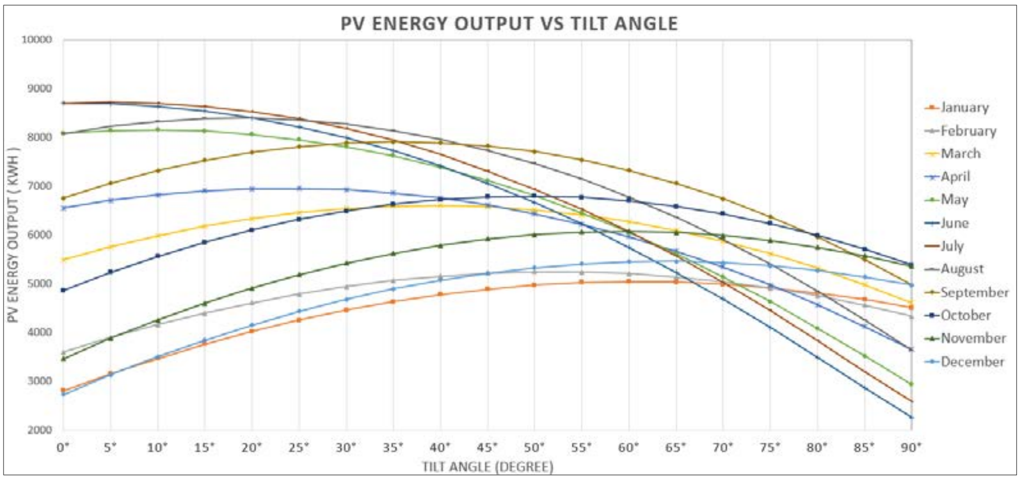

Figure 5: Monthly collected PV energy versus tilt angle

5.2. *YEARLY OPTIMUM TILT ANGLE*

As it has been discussed before that the cost of tracked PV panels is high, so the fixed mounting system was used in this research. For yearly fixed mounting panels, a yearly optimum tilt angle should be founded to maximize the output power. For this step, the tilt angle was modified from 0 to 90 degrees in steps of 1 degree, and the PV output energy was recorded for each angle using the PVGIS simulation program in order to determine the annually optimum tilt angle. The result shows that the angle of 32.7° is the yearly tilt angle of Duhok city. Fig. 6 displays the yearly collected PV energy absorbed from sun radiation by the 50 KWp PV array. It was noticed that the output PV energy increased with increasing the tilt angle until it reached the maximum energy at the optimum tilt angle. Whereas further increasing the tilt angle, the output energy reduced gradually. The maximum yearly PV output energy obtained at the optimum tilt angle which was 79760.9 KWh (Fig. 8) and the minimum output energy was 49266.65 KWh at the tilt angle of 90°. On the other hand, Fig. 7 presents the variation of yearly in-plane irradiance fallen on the PV panels at different tilt angles.

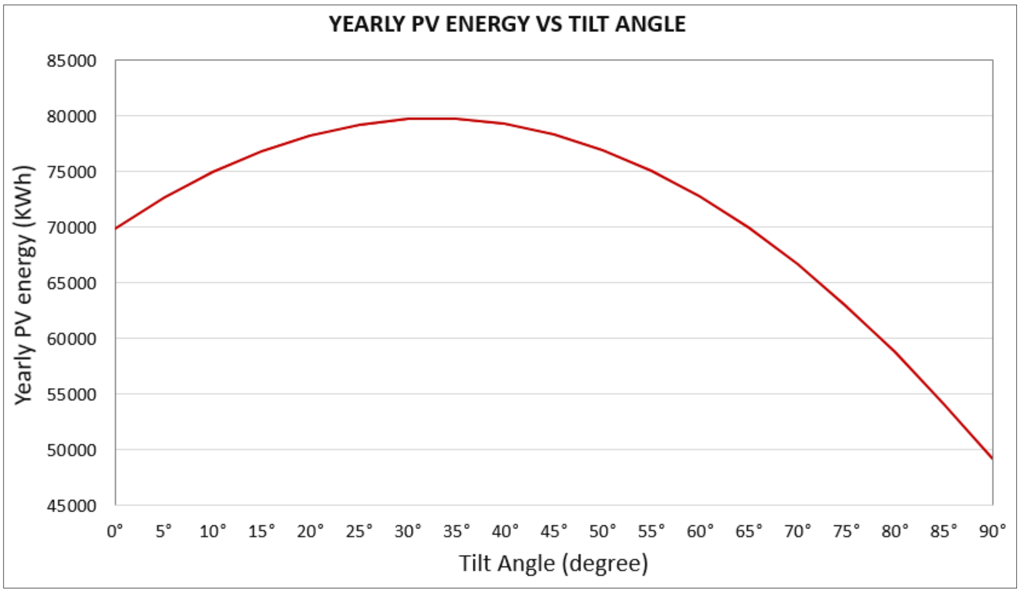

Figure 6: Yearly collected PV energy versus tilt angle located in Duhok

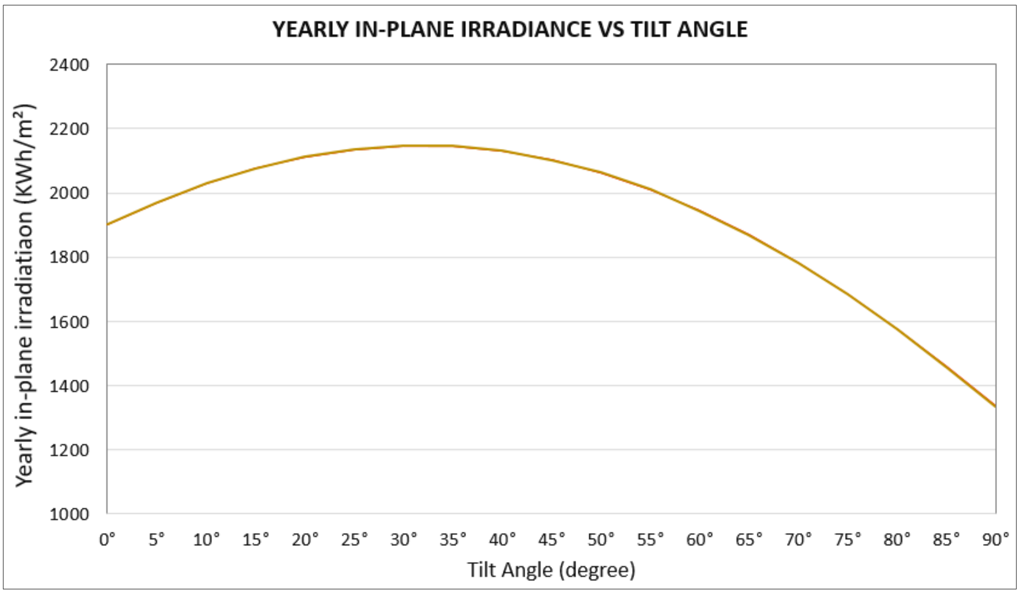

Figure 7: Yearly collected In-plane Irradiation vs tilt angle located in Duhok

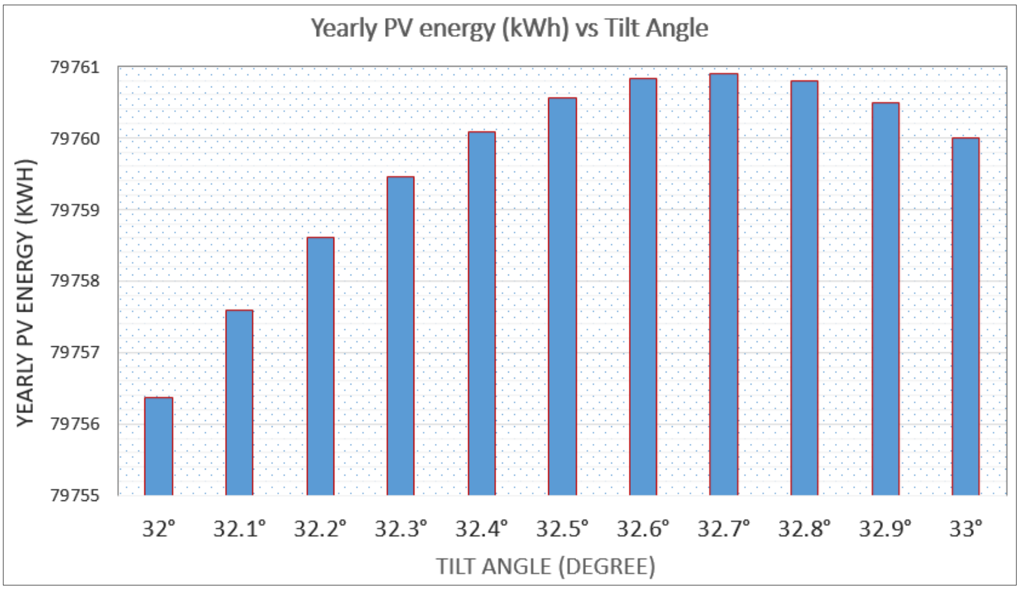

Figure 8: Yearly collected power energy vs tilt angle located in Duhok city

5.3. *OPTIMUM TILT ANGLE WITH DIFFERENT PV TECHNOLOGIES*

After determining the optimum tilt angle of the PV system in Duhok city, the optimum tilt angle was used with various PV types which were Crystalline Silicon, Cadmium Telluride (CdTe), and Copper Indium Selenide (CIS). In order to find the best PV type to be installed in Duhok city. In other words, to find which PV technology is more appropriate for Duhok weather. The results showed that solar radiation was the same for the three PV technologies as it is not depending on PV types (Fig. 9). Contrary, the output PV energy influenced by changing PV technology. The CdTe and CIS technologies produced more power than Crystalline Silicon in summer months as shown in fig. 10. While in winter Crystalline Silicon produced higher power than CdTe and CIS. However, as an overall result, the CdTe produced higher yearly PV output energy which was 81766.96 kWh. Whereas, CIS and Crystalline Silicon PV panels generated yearly energy of 79935.12 kWh and 79760.9 kWh respectively.

Which means that the CdTe is more appropriate than CIS and Crystalline Silicon for Duhok weather, followed by CIS type.

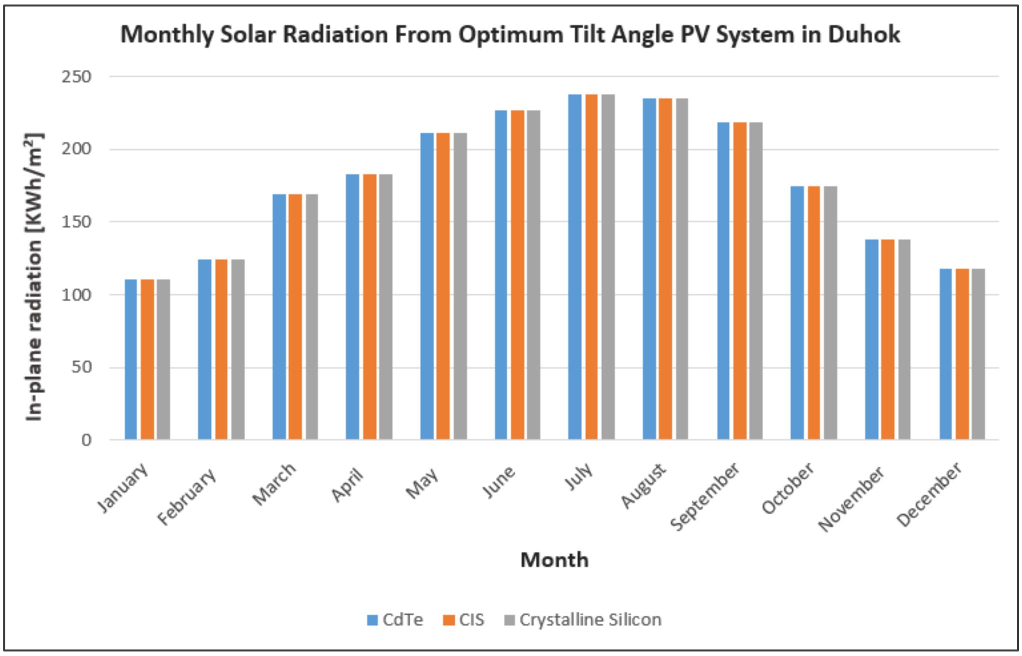

Figure 9: Monthly solar radiation with different PV technologies

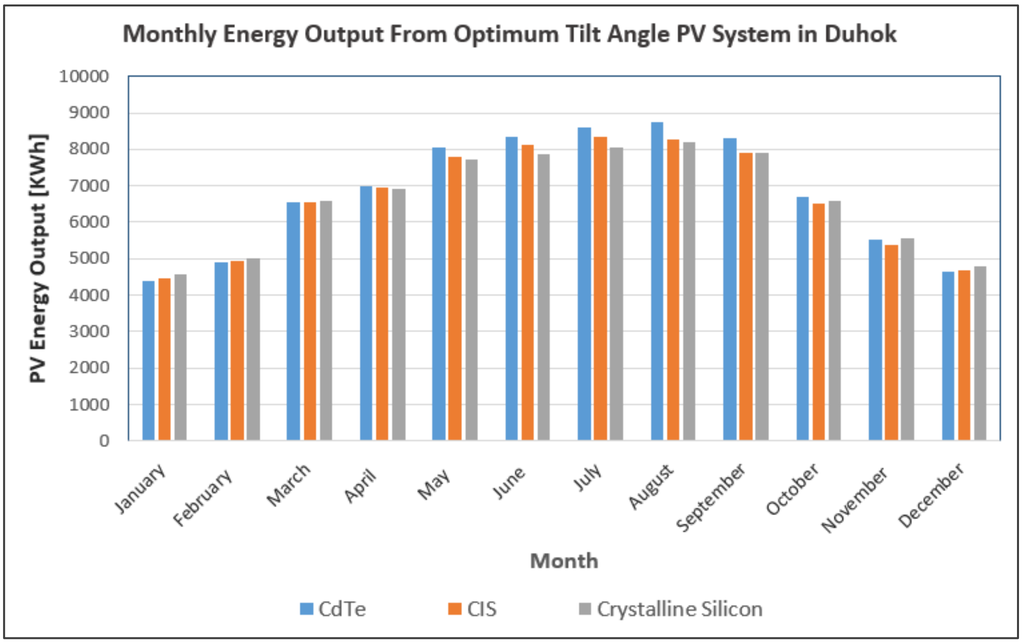

Figure 10: Monthly output energy with different PV technologies

6. CONCLUSION

This research has examined the tilt angle of 50 KWp solar systems to be installed in Duhok city in the Kurdistan region of Iraq, as well as the performance of the system with different PV types. The tilt angle was varied from 0 to 90 degrees (with increments of 1 degree) using a simulation tool to choose an optimum angle. The results demonstrated that the monthly optimum tilt angles were under 30° in summer while in the winter the angles were above 50° in Duhok. Due to the fact that the sun is near to the horizon in summer. Thus, the fixed mounting solar systems can be modified monthly or seasonally. However, if a constant tilt angle is selected for the whole year between photovoltaic panels and the horizontal plane for solar energy projects in Duhok city, the tilt angle of 32.7° is the most appropriate angle according to the current results. In terms of PV technologies, CdTe gives higher yearly output energy than other types. In the future, the amount of absorption of the solar irradiance can be increased by choosing an optimum azimuth angle alongside the optimum tilt angle for the aforementioned city.

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