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Conference Paper · November 2015

DOI: 10.1109/ELECO.2015.7394517

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Calculation of Optimum Fixed Tilt Angle of PV Panels Depending on Solar Angles and Comparison of the Results with Experimental Study Conducted in Summer in Bilecik, Turkey

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Abstract

Sunlight incidence angle varies throughout the year due to the rotation of the earth around its own axis and its elliptical orbit. While sunlight falls to the earth with steep angle in summer in the Northern Hemisphere, it falls with shallow angle in winter. Sunlight should fall with steep angle to extract maximum power from PV panels. Therefore optimum fixed tilt angles of PV panels should be changed monthly and seasonally. In the mathematical analysis of the study, the monthly, seasonal and the annual optimum fixed tilt angles of PV panels depending on solar angles are calculated for Bilecik city. In the experimental study, optimum fixed tilt angles for May, June, July and August are determined by PV panels placed at 10º, 20º, 30º, 40º, 50º and 60º tilt angles. The mathematical analysis results are compared with the experimental results.

1. Introduction

Fossil fuels are generally used to meet the electricity needs. However, energy policies of the countries are directed at encouraging the use of renewable energy sources since fossil fuels will be exhausted in the near future, they give harm on the environment and they have rising prices. Among the renewable energy sources, the solar energy has gained popularity for energy demand recently and has been prompted. Therefore, the costs have reduced and studies in this field have increased [1, 2]. Solar energy is among the most plentiful renewable energy sources in Turkey. Turkey is located between 36º-42º north latitude and Turkey's yearly average total sunshine duration is 2640 h and the yearly average solar radiation is 1311 kWh/m². Therefore, Turkey is well situated in terms of solar energy potential [3].

PV panels are devices made by semiconductor materials and they directly convert the sunlight falling on them to electrical energy [4]. PV panels should be placed in a way to form a tilt angle with the horizontal plane to extract maximum power from PV panels and so sun lights can fall with steep angle. The radiation level falling on the panels is dependent on the latitude and longitude of the location where PV panels are placed. While sun lights fall with steep angle at noon, they fall with a shallow angle in the mornings and after noon. Therefore the tilt angle of the panels varies in different regions and they differ monthly, seasonally and annually [5, 6]. The monthly and seasonal changes of the tilt angles of the panels should be studied by mathematical calculations and should be supported by experimental results. In this study, tilt angles of PV panels were calculated monthly and seasonally and were compared with experimental results carried out during summer period. The study was carried out in Bilecik city situated at the west part of Turkey and located at 40º (Ø=40º) latitude. The daily average sunshine duration in Bilecik city is 6.6 h and yearly average total sunshine duration is 2424 h. The daily average solar radiation is 3.87 kWh/m² and the yearly average total solar radiation is 1412 kWh/m² [7, 8]. Therefore, according to the sunshine duration and solar radiation values Bilecik city is found to be well situated with respect to solar energy potential.

In literature, Kaldellis and Zafirakis [2] carried out a study to evaluate the performance of PV panels with different tilt angles during the summer period in Athens, Greece. Optimum tilt angle was found to be 15º (±2.5º) and the results were verified theoretically. Gunerhan and Hepbasli [3] determined the optimum values of tilt angles for solar collectors installed in Izmir, Turkey and they used the experimental data to apply the model. George and Anto [4] estimated the optimal tilt angle of PV panels installed in Kerala, India using geographic factor method, clearness index method and declination angle method. The methods were compared with the experimental results. Rouholamini et al. [9] estimated the total solar radiation on a tilted angle and calculated the output energy of PV panels using a mathematical model. Kacira et al. [10] used a mathematical model to determine the total solar radiation of the tilted PV surface and optimum tilt angles of PV panels installed in Sanliurfa, Turkey. Also, they examined the energy gain of two-axis solar tracking and compared with a fixed PV panel. Benghanem [11] conducted the study based on measured values of daily global and diffuse solar radiation to determine the optimal tilt angle of the solar panel. The study was conducted in Madinah, Saudi Arabia. It was found that annual optimum tilt angle was nearly equal to the latitude of the city. Daut et al. [12] calculated the tilt angle and global solar irradiance on PV module in Perlis, Northern Malaysia using a mathematical model. Skeiker [13] estimated the solar radiation on a tilted surface and determined the optimum tilt angle and orientation for the solar collector installed in Syrian zones using a mathematical model. Despotovic and Nedic [14] determined the yearly, biannual, seasonal, monthly, fortnightly and daily optimum tilt angles of solar collectors for Belgrade by searching the values for which the solar radiation on the collector surface is maximum for a particular day or a specific period. Yadav and Chandel [15] examined the various methods used for determining the tilt angles of PV panels.

It is seen that the experimental studies in literature focused on the global and diffuse solar radiation calculation to determine the optimum tilt angle. In the study, the monthly optimum tilt angle was determined by examining the energy amount of PV panels placed at 10º, 20º, 30º, 40º, 50º and 60º tilt angles. Raspberry Pi was used for the store, backup, analysis of the data in the computer environment and to transfer the data to a web page. The some electrical data such as voltage, current and power of PV panels are watched alive from 05:00 to 21:00 every day by the web server set up on Raspberry Pi. The experimental data obtained for summer period was compared with the mathematical analysis results.

This paper is organized as follows: Section 2 presents the solar angles to be used in the mathematical analysis. In section 3, the formulas about solar angles are drawn in Matlab programme and the analyses of the monthly, seasonal and the annual optimum tilt angles are conducted. Section 4 gives information about the experimental set up and analyses results. The experimental results are compared with analysis results in the conclusion part.

2. Solar Angles

The solar radiation reaching a per square meter in the outer atmosphere is 1367 W/m². However, some of the sun lights falling on the earth are absorbed and reflected back by the atmosphere and the clouds. Some angles form between the sunlight falling on the earth and the surfaces. The position of the sun at different periods is determined by the solar angles. Moreover, solar angles are used to track the movement of the sun in a day. The rotation of the sun varies depending on the latitude and longitude of the location. Therefore, the solar angles will be different for the locations at different latitude and longitude during the same period. So, the solar angles must be known to determine the position of the sun [9, 16, 17].

2.1. Latitude, Declination and Hour Angles

The latitude angle (Ø) is the angle forming according to the equator center. The north of the equator is positive and the south of the equator is negative and it varies between -90º ≤ Ø ≤ 90º. The longitude and the latitude angles are used to define the any location on the surface of the earth. Turkey is located at 36º-42º north latitude and at 26º-45º east longitude [1, 17, 20].

Declination angle (δ) is the angle between the sun lights and equator plane. Declination angle occur due to 23.45 degree angle between earth's rotational angle and the orbital plane. It is positive at north and varies between -23.45º ≤ δ ≤ 23.45º. Declination angle is at its highest point on 21th June (23.45º) while it is at its lowest point (-23.45º) on 22nd December in winter. Sun lights fall on the equator with steep angle twice a year. This condition is called as equinox. Vernal equinox is on 20 March and autumnal equinox is on 23 September. Daytime and night time durations are equal on equinox dates and the declination angle is 0. Declination angle is shown in Figure 1.

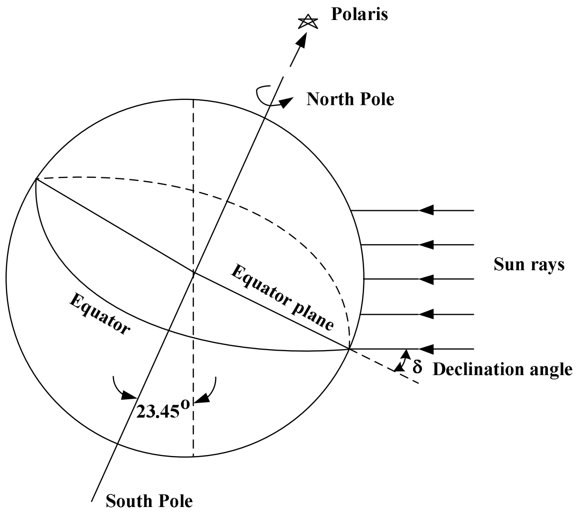


Fig. 1. Declination angle

Declination angle is calculated by the following equation.

$$\delta = 23.45 \sin\left[360 * \frac{(284+n)}{365}\right] \qquad (1)$$

Where n represents the day of the year and 1st January is accepted as the start [16, 18, 20, 21]. The yearly variance of declination angle is drawn in Matlab programme by declination angle formula. The yearly variance of declination angle is shown in Figure 2.

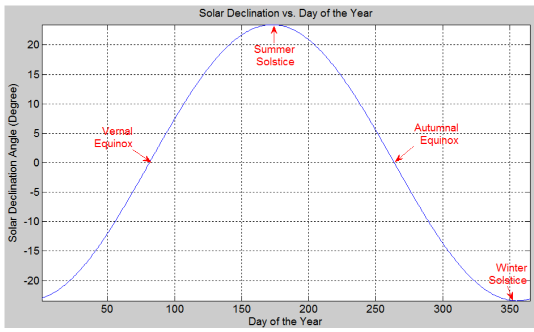


Fig. 2. The yearly variance of declination angle

Hour angle (ω) is the angle between the longitude of sun lights and the longitude of the location. The angle before noon and after noon are taken as (-) and (+) respectively. This angle is 0 at noon. The hour angle is defined as the difference between noon and the desired time of the day. This angle is calculated by multiplying this difference by 15 fixed number. This fixed number is the angle of 1 hour rotation of the earth around the Sun. An expression to calculate the hour angle from solar time is

$$\omega = 15(t_s - 12) \qquad (2)$$

where t_s is the solar time in hours [16, 17, 20].

2.2. Zenith, Elevation and Azimuth Angles

Zenith angle (θ_z) is the angle between the line to the sun and the vertical axis. The basic solar angles existed on the earth's surface are shown in Figure 3.

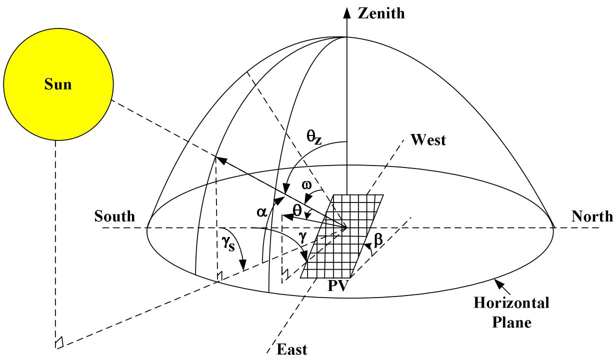


Fig. 3. The basic solar angles

Zenith angle is 90º during sunrise and sunset whereas it is 0º at noon. Zenith angle is calculated depending on the other angles [14, 16, 20].

$$\cos\theta_z = \cos\delta.\cos\phi.\cos\omega + \sin\delta.\sin\phi \qquad (3)$$

Solar elevation angle (α) is the angle between the line to the sun and the horizontal plane. This angle is the complement of the zenith angle 90º. Elevation angle is calculated by the following equation.

$$\alpha = 90 - \theta_z \qquad (4)$$

Solar azimuth angle (γ_s) is the angle between the north or south position of the sun and the direct solar radiation. This angle is assumed to be (-) from south to east and to be (+) from south to west. (γ_s) is 180º at noon. Azimuth angle is calculated by the following equation.

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

Surface azimuth angle (γ) is the angle between the projection of the normal to the surface on a horizontal plane and the line due south. This angle is 0 in south, negative in east (-) and it is positive (+) towards west. It varies between -180º and 180º [16, 20].

2.3. Incidence and Tilt Angles

Incidence angle (θ) is the angle between the radiation falling on the surface directly and the normal of that surface. If incidence angle is steep to the sun lights, it is (θ=0º). On the other hand if this angle is parallel to the sun lights, it is (θ=90º). The incidence and tilt angles are shown in Figure 4.

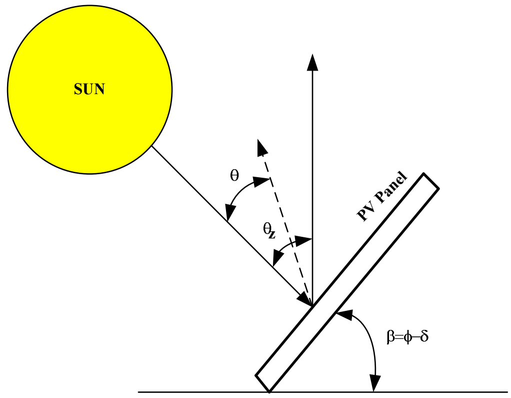


Fig. 4. Incidence and tilt angels

Incidence angle is used in the design of solar energy systems. Incidence angle is calculated by the following equation [2, 16, 20].

$$\theta = \cos^{-1}\left[\cos(\delta).\cos(\phi).\cos(\omega) + \sin(\delta).\sin(\phi)\right] \qquad (6)$$

Tilt angle (β) is the angle between the panels and the horizontal plane. This angle is south oriented in the Northern Hemisphere and north oriented in the Southern Hemisphere. Tilt angle varies between 0º ≤ β ≤ 180º. When a plane is rotated about horizontal east-west axis with a single daily adjustment, the tilt angle of the surface will be fixed for each day and is calculated by the following equation.

$$\beta = |\phi - \delta| \qquad (7)$$

On the other hand, when the plane is rotated about a horizontal east-west axis with continuous adjustment, the tilt angle of the surface will be calculated by the following equation.

$$\tan\beta = \tan\theta_z.|\cos\gamma_s| \qquad (8)$$

For the rotation of a plane about a horizontal north-south axis with continuous adjustment, the tilt angle of the surface will be calculated by the following equation [16, 20].

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

3. Mathematical Analysis and Simulation Results

The tilt angle of each day in a year for Bilecik city written in Matlab programme using the formulas about solar angles is shown in Figure 5. The approximate optimum tilt angle points are also shown in the figure.

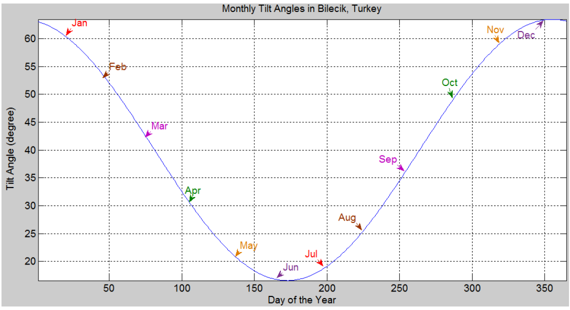


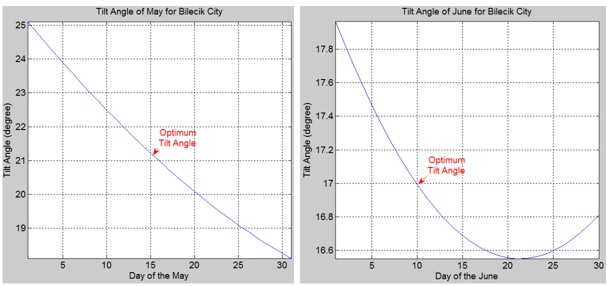
Fig. 5. The yearly variance of tilt angle

The monthly approximate average values are calculated using the daily data. The monthly optimum fixed tilt angles are shown in Table 1.

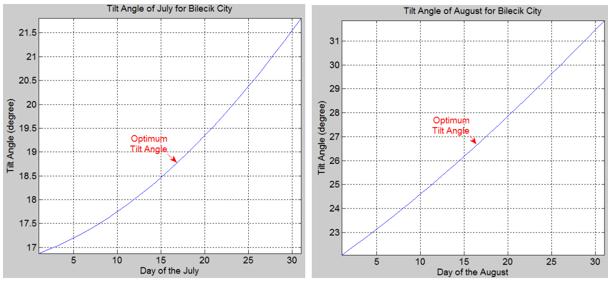
Table 1. Monthly optimum fixed tilt angles

Jan	Feb	Mar	Apr	May	Jun
60.88º	53.39º	42.38º	30.51º	21.20º	16.92º
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
18.88º	26.67º	37.95º	49.79º	59.01º	63.08º

The optimum fixed tilt angle is calculated seasonally as 48.93º, 31.37º, 20.86º and 59.11º for autumn, spring, summer and winter seasons respectively. The yearly optimum tilt angle for Bilecik city is calculated as 39.98º and found to be nearly equal to the latitude of Bilecik city. Gunerhan and Hepbasli [3] and Benghanem [11] found in their study that the yearly optimum tilt angle was nearly equal to the latitude of the location where they conducted the study. The tilt angle of the summer season is found to be minimum and the tilt angle of the winter season is found to be maximum according to the seasonal optimum tilt angle calculation depending on solar angles. The monthly tilt angle is found to be minimum for June (16.92º) and maximum for December (63.08º). The mathematical results of the study are similar with the results obtained by Kacira et al. [10]. Kacira et al. conducted their study in Sanliurfa city located at 37º latitude in Turkey. The seasonal tilt angles depending on solar angle are found to be as βopt=Ø+10º, βopt=Ø-10º, βopt=Ø-20º and βopt=Ø+20º for autumn, spring, summer and winter respectively. The obtained results show that the tilt angle for Bilecik city for autumn and spring season and winter and summer season should be βopt=Ø±10º and βopt=Ø±20º respectively. The experimental study was carried out in May, June, July and August and the tilt angles of these months are shown in Figure 6. The optimum tilt points are shown in the figure.



(a) (b)



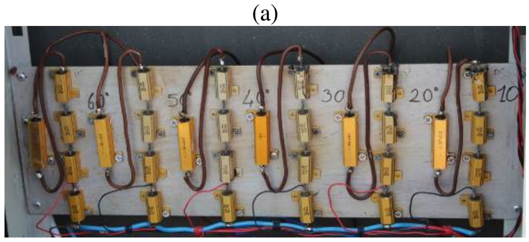
(c) (d)

Fig. 6. Optimum tilt angles (a) May (b) June (c) July (d) August

4. Experimental Setup and Analysis Results

Six PV panels with the same features were placed on the roof of Bilecik Seyh Edebali University Engineering Faculty at different tilt angles. The experimental setup is shown in Figure 7.

(a)



(b)

Fig. 7. Experimental setup (a) PV Panels (b) Loads

A Perlight 100 Wp PLM-100P/12 model polycrystalline PV panel is used for the system. Catalog data of the panel is shown in Table 2.

Table 2. Catalog data of the PV panel

PLM-100P/12 at 1000 W/m² and 25ºC	
Maximum Power, P_{max}	100 W
Voltage of Maximum Power Point, V_{mpp}	17.7 V
Current of Maximum Power Point, I_{mpp}	5.65 A
Voltage of Open Circuit Point, V_{oc}	22 V
Current of Short Circuit Point, I_{sc}	6.21 A

The analog voltage data obtained from PV panels is converted to digital data by a microprocessor. The average value of the obtained digital data is taken every 10 minutes and the data is stored in a SD card placed on Raspberry Pi. The microprocessor and Raspberry Pi used in the system are shown in Figure 8.

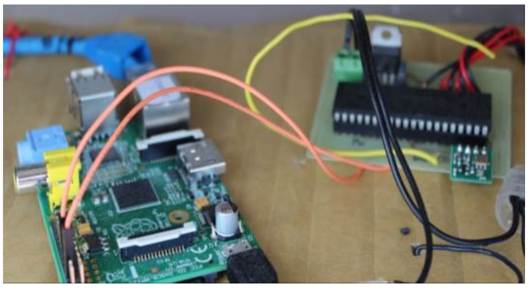


Fig. 8. The microprocessor and Raspberry Pi used in the system

The voltage data of the PV panels are just measured in the system. The current and the power values of the PV panels are calculated by an algorithm written with Raspberry Pi programming language. As it is shown in Figure 9, the average voltage, current and power values of the panels are watched alive daily on a web page.

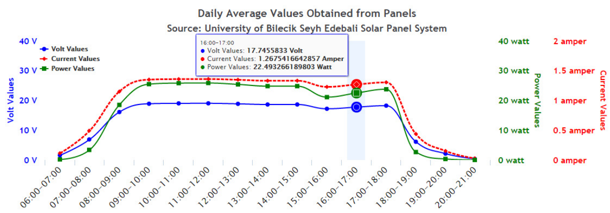


Fig. 9. Daily average voltage, current and power obtained from PV panels

The daily voltage and current values of each PV panel are shown in Figure 10.

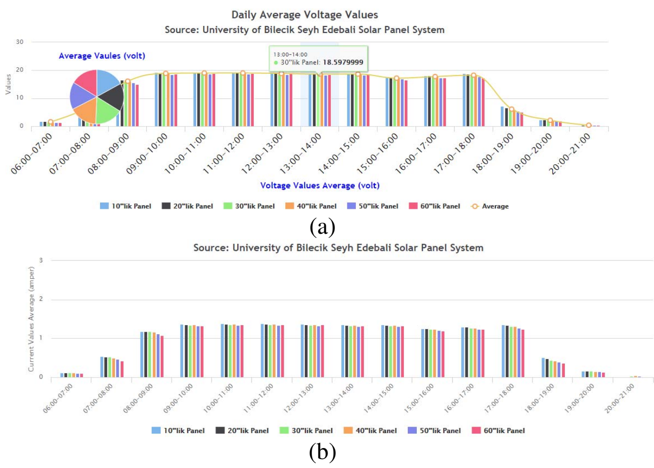


Fig. 10. The daily values of each panel (a) voltage (b) current

Moreover the stored data can be seen in a long duration with daily date and time data. The power amount for May, June, July and August produced by PV panes are shown in Figure 11 by percentage and in pie charts. The power amount produced by each panel at different tilt angle is shown in Table 3 by percentage.

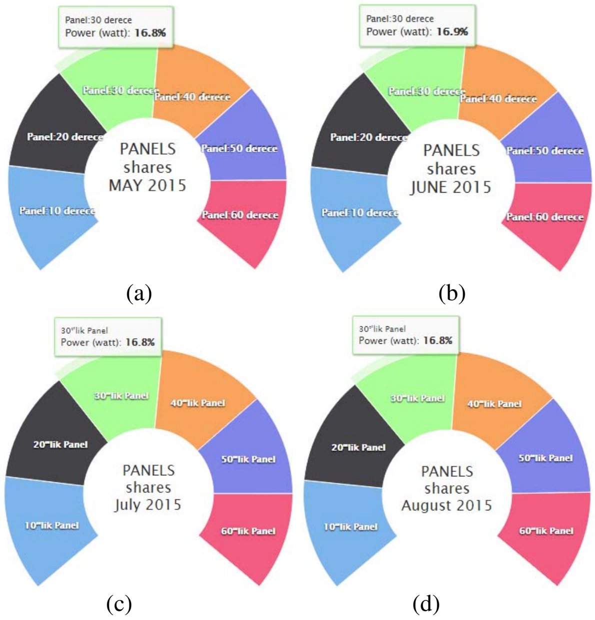


Fig. 11. The power amount produced by each panel (a) May (b) June (c) July (d) August

Table 3. The power amount produced by PV panels (in percentages)

	May	June	July	August
10º	17.9%	17.9%	18%	17.6%
20º	17.1%	17.4%	17.3%	17.1%
30º	16.8%	16.9%	16.8%	16.8%
40º	16.8%	16.7%	16.7%	16.8%
50º	15.9%	15.7%	15.8%	15.9%
60º	15.4%	15.1%	15.4%	15.7%

The experimental results showed that the more power is extracted from the panel with 10° tilt angle during summer period compared with the other panels. The lowest power is extracted from the panel with 60° tilt angle. It is found that the panel with 10° tilt angle produced more energy by 2.5% rate compared to the panel with 60° tilt angle. The manufacturers can benefit from the energy amount corresponding to this difference especially for high power grid connected or off-grid systems. Moreover this energy amount can make a great contribution to the economy. The results show that the fixed tilt angle of PV panels should be 10° during summer period for high power solar energy applications in Bilecik city. Therefore, the maximum power can be extracted from PV panels and a great amount of energy save will be provided.

5. Conclusions

The tilt angles of PV panels should be adjusted monthly, seasonal or the yearly to extract the maximum energy from PV panels. In this study the tilt angles for Bilecik city are calculated using solar angles and the mathematical values of the tilt angles are compared with the experimental results. The results are shown in Table 4.

Table 4. The comparison of the experimental results and the mathematical results

Month	Optimum Tilt Angle (degree)	
	Mathematical Value	Experimental Value
May	21.20º	10º
June	16.92º	10º
July	18.88º	10º
August	26.67º	10º

The results show that the experimental results differ from the mathematical results by approximately 11º. The difference is caused by some environmental factors such as temperature, dust and dirt. The increase in temperature decreases the voltage of PV panels and so decreases the efficiency of the panels. Some factors such as dust, dirt etc. have a great effect on the efficiency of the panels. It is concluded that the environmental factors such as dust should be considered to determine the optimum tilt angle of the panels to extract maximum power from PV panels.

Acknowledgements

This research was supported by Bilecik Seyh Edebali University Research Projects Fund (No: 2014-01.BIL.03-02). The authors would like to thank for support.

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