INVESTIGATING THE OPTIMUM TILT ANGLE OF PV MODULES IN AL-SHEROUK CITY, CAIRO

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Abstract: *Energy is a crucial element that can ensure the quality of life for citizens. The consumption of energy by citizens is increasing rapidly, and future existence also became reliant on the sufficient availability of energy and its sources. Nevertheless, energy consumption is becoming a major concern due to the increase in usage rates and the lack of sufficient renewable sources of energy. Nowadays, the technological advancement that lies in the use of photovoltaic panels (PV panels) can help in generating energy and take the advantage of the sun especially in Egypt. The usage of PV's relies on multiple factors that can ensure the highest potential generation of energy. Therefore, several studies investigated these factors including the optimum titling angle that can be different according to the location and orientation of the panel. Modifying the titling angle can play a significant role in generating high rates of power depending on the measurements and calculations. The aim of this paper was to investigate the efficient titling angle that can be used for PV panels that are installed in Al-Sherouk City in Egypt. The methodology involved the implementation of an experimental investigation that is based on position 2 similar PV panels to estimate the power generation over a period of 2 days from 9 am to 4 pm. The findings have shown that the theoretical and experimental results were similar, and the optimum tilting angle was determined to range between 54.7 degrees and 8.16 degrees. The study demonstrated the differences between an adjusted and a fixed angle, and the variable titled angle can generate more energy than the fixed one. This paper contributes to the body of knowledge by presenting the significance of a variable tilting angle to generate more power than relying on a fixed angle as demonstrated by many previous studies.*

Keywords: *solar energy, photovoltaic panels, renewable energy, solar energy in Egypt, optimum tilt angle*

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Introduction

People should pay more attention to renewable energy due to the lack of sufficient energy sources and the positive impact of using a renewable source of energy. It is important for developing and developed countries to consider finding new solutions to increase in prices of oil, increase in electricity demands, high rate of greenhouse gas emissions, and even global warming [4]. Solar energy is categories as a renewable source of energy which has been developing to an extent scale due to limitations in energy transmission [2]. Normally, there are multiple benefits of solar energy over the use of fossil fuels such as reduced carbon emissions, cleaner air, and can generate power over a long period of time. Hence, due to the huge increase in electricity consumption, researchers are more concerned about developing solar energy developments with excellent efficiency, less environmental pollution, and with proper investments cost [2].

The overall global energy consumption in 2014 was recorded to be around 160310 million MWh, and it was estimated that this value is expected to keep on increasing to reach around 240318 million MWh by 2040 [6]. It was recorded in 2010 that the electrical generation systems that are based on renewable energy increased by 20% from the overall electricity generation, and this value will keep on increasing until it reaches 31% by 2035 [3]. The use of renewable energy can help in generating around 57% of global electricity supply by 2025 [3]. Eventually, the dependency on solar energy for electricity production is growing around the globe. Hence, solar energy production should be developed and promoted due to the negative impact of conventional energy production [1]. During the past few years, a huge amount of investment was focused on the improvement in solar energy production which helped countries to reach better technological advancement and cost-effective production of energy [1].

Shu et al [5] investigated the optimum tilt angle for solar panels in Kitakyushu City. There are multiple variables that were considered in the experiment including the sensitivity of optimum tilting angle, radiation rates, reflection rates, and declination of solar. The results demonstrated that the 35 degrees tilting angle had the most intensity of radiation between December to November of the following year. Another important factor to be considered is that if the latitude gets higher than the optimal angle might increase.

Tlijani et al [7] conducted a study regarding the optimization of tilt angle of solar panels that are located in Tunisia. The research focused on the comparison between the experimental and theoretical results using Matlab simulation analysis. The angles used in the study were 0, 30, 45, 60, and 90 degrees and the panel was positioned once in the west, then changed to south and east. The first panel had dimensions of 370*295*15 mm and was placed at a temperature of 25 degrees Celsius. The second one had a dimension of 215*225*18 mm and was located in the same way as the first one. The findings of this study demonstrated that climate conditions and the location of the solar panel might impact the total power generated by the system. This paper discussed the potential optimum tilt angle for PV to generate optimum power and energy.

Materials and Methods

Procedure of Calculations (Table 1)

1. The first step taken in the calculations was determining the deflection angle as shown in the equation below:

Deflection angle equation
$$\delta = 23.45\ \sin\left(360 \cdot \frac{284 + n}{365}\right) \tag{1}$$

2. B is then calculated using the following equation

$$B = n - 1\frac{360}{365}$$

3. True solar time is then measured using this equation

$$E = 229.2 \cdot 0.000075 + 0.001868 \cdot \cos B - 0.032077 \cdot \sin B - 0.014615 \cdot cos2B - 0.04089 \cdot \sin 2B)$$

4. After calculating the B, the solar time (ST) is then calculated, ST is the time where the measurements are taken (14:00pm). This time was basically chosen because the radiations from the sun were considered the highest during the entire day time. I_{st} is the standard longitude of time zone, and I l_{oc} is the longitude of the location. l_{oc} of the chosen location "Al-Sherouk City" is taken as 31.610584.

$$Solartime - ST = 4 \cdot (l_{st} - l_{loc}) + E$$

5. Hour angle is then measured using the following equation, where the t_s is known as the solar time.

Hour angle
$$\omega = 15(t_s - 12) \tag{2}$$

6. Zenith angle is then measured as follows, where ϕ is the latitude and taken as 30.1187 according to Al-Sherouk City location.

Zero angle
$$\cos\theta_z = \cos\delta \cdot cos\emptyset \cdot cos\omega + sin\delta \cdot sin\emptyset \tag{3}$$

7. The solar elevation angle is then measured using this equation.

Calculating the zero elevation angle
$$\alpha = 90 - \theta_z \tag{4}$$

8. Solar Azimuth angle is the next to be calculated.

Solar azimuth angle $$\gamma_s = cos^{-1}[(\sin(\alpha) \cdot \sin(\emptyset) - \sin(\delta)/\cos(\alpha) \cdot \cos(\emptyset) \quad (5)$$

9. Incidence angle is then measured using the following equation.

Incidence angle $$\theta = cos^{-1}[\cos(\delta) \cdot \cos(\emptyset) \cdot \cos(\omega) + \sin(\delta) \cdot \sin(\emptyset) \quad (6)$$

10. Then the tilt angle is measured as follows.

Calculation for the tilt angle $$\beta = |\emptyset - \delta| \quad (7)$$

Table 1. Measured calculation of all above parameters

Days / parameters	δ	B	E	Solar time	W	Cos zenith angle	Zenith angle	Solar elevation angle (α)	Without (cos) inverse	Solar azimuth angle (ϒs)	β
1	-23.01	0.00	-2.90	14.16	32.34	0.46	62.37	27.63	0.61	52.45	54.62
2	-22.93	0.99	-3.35	14.16	32.45	0.46	62.35	27.65	0.61	52.53	54.54
3	-22.84	1.97	-3.39	14.17	32.56	0.46	62.33	27.67	0.61	52.60	54.45

Calculating the solar irradiance

The theoretical calculations are based on previously obtained results of using solar panels in the same locations investigated in the experimental part of this study. The below are the data collected from specific dates in 2017 (Table 2).

Table 2. Calculation of Solar Irradiance of tilted angle "S"

Date	A	B	C	Zenith angle	Tilt angle	Gbn	Gd	G	rb	F	Ground reflectivity	Gt
17/1/2017	1232.46	0.1416	0.057	61.31	52.23	917.46	52.93	493.38	1.02	0.988	0.2	523.4
16/2/2017	1216.58	0.1436	0.059	55.19	44.57	945.87	56.44	596.44	1.01	0.991	0.2	622.8
16/3/2017	1190.18	0.1538	0.009	45.99	34.03	953.76	52.04	714.69	1.00	0.994	0.2	733.2
15/4/2017	1144.68	0.1753	0.091	35.69	22.2	922.41	84.83	834.1	0.99	0.989	0.2	844.60
15/5/2017	1109.4	0.1928	0.116	28.87	12.82	890.17	103.43	882.97	0.98	0.986	0.2	884.13
11/6/2017	1092.84	0.2020	0.129	27.28	8.52	870.56	113	886.74	0.98	0.983	0.2	884.09
17/7/2017	1085.4	0.2067	0.135	29.76	10.43	855.39	116.10	858.68	0.98	0.981	0.2	859.78
16/8/2017	1103.45	0.1967	0.124	33.9	18.16	865.15	107.50	825.59	0.99	0.983	0.2	834.43
15/9/2017	1142.48	0.1816	0.097	40.06	29.39	901.11	88.13	777.82	0.99	0.987	0.2	795.64
15/10/2017	1183.8	0.1634	0.076	48.3	41.21	925.98	71.11	687.10	1.00	0.989	0.2	713.75
14/11/2017	1213.68	0.1514	0.052	56.51	50.52	922.30	60.18	569.10	1.01	0.988	0.2	601.07
10/12/2017	1228.23	0.1445	0.059	61.24	54.66	909.47	53.84	491.42	1.02	0.987	0.2	524.11

Table 3 represents the average day for each month in order to measure the solar irradiance in this specific day.

Table 3. Average day for each month

Month	N for ith day of month	For average day of month		
		Date	n	δ
January	i	17	17	-20.9
February	31 + i	16	47	-13
March	59 + i	16	75	-2.4
April	90 + i	15	105	9.4
May	120 + i	15	135	18.8
June	151 + i	11	162	23.1
July	181 + i	17	198	21.2
August	212 + i	16	228	13.5
September	243 + i	15	258	2.2
October	273 + i	15	288	-9.6
November	304 + i	14	318	-18.9
December	334 + i	10	344	-23

Calculating Power Output and Efficiency of Panel:

The total power output had to be measured for the panel during the experiment for the whole month according to the data obtained from the British University in Egypt as shown in Table 4.

Table 4. Measurements of power for each month

		Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec
Power (KWH/month)	Optimum	57.5	53.1	58.4	55	56.4	54.6	56.0	55.5	53.9	55.9	53.7	55.6
Power (KWH/month)	Tilt 30	52.4	50.9	58.2	54.3	53.2	50.0	52.1	54.0	53.9	54.6	49.6	49.6

Maximum efficiency equation

$$\eta_{max}(maximum\ efficiency) = \frac{P_{max}\ (maximum\ power\ output)}{(E(incident\ radition\ flux) \cdot A_c(area\ of\ collector)} \quad (8)$$

Experimental Procedure

The experimental procedure that was followed in this research focused on comparing the generated results between the theoretical analysis and experimental results and indicate any variations in the generated results (Fig.1). The experiment included the use of 2 identical panels that are directed to the south direction using multiple tilt angels that ranged from 0 degrees, 15, 30, and until 45 degrees. These panels were positioned on the top of the British University in Egypt.

Fig. 1. *Used PV panels in the experiment*

The main objective was to indicate the solar radiation and generated power from the panels during an annual measurement where the size of the PV module used was 1.65 · 0.953 meters and the overall area is 1.57 m^2. In addition, the maximum power within the panel was 280W. The type of the used PV panel is Monocrystalline Silicon Module. The field observations were decided to be undertaken during 2 various days which are 24/5/2018, and 26/5/2018. The PV panel was installed and kept on recording starting from 9 am until 4 pm, while the readings are taken each half an hour. The field procedure consisted of the following steps:

1. The first step was to properly clean the panels in order to remove any sand particles, dust, or any objects that might affect the collection of solar radiation by the panel.
2. Then, the panels were adjusted into 2 different angles at which to determine the optimum angle that could generate the highest solar radiation.
3. PV system analyzer was adjusted to include the data and specifications of the panel used.

Experimental Results

The results demonstrated that 15 degrees tilt angle generated the highest potential power output from the panel as shown in Fig.2.

Fig. 2 shows the experimental readings that were taken during the 2 days of field observations starting from 9am until 4pm. Certain radiations were chosen after the experiment in order to estimate the power energy while the most optimum angle will usually yield the highest power. In the theoretical results the optimum angle was estimated to be from 10 to 11 degrees as shown in Fig. 3. The highest angles that provided most power were recorded in 0, 15, 30, 45 degrees respectively. Therefore, the experimental and theoretical results were quite close according to the generated optimum tilt angle (Fig.3).

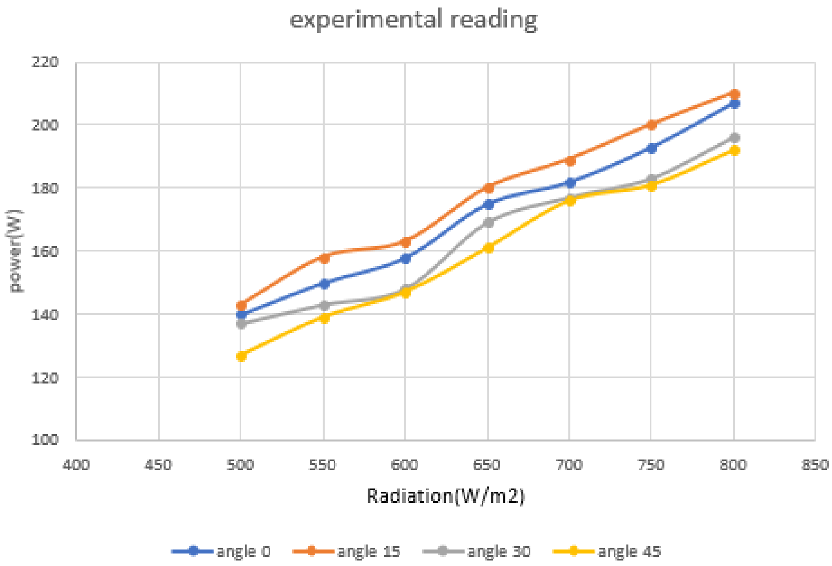

Fig. 2. *Experimental readings for the different tilt angles and power outputs*

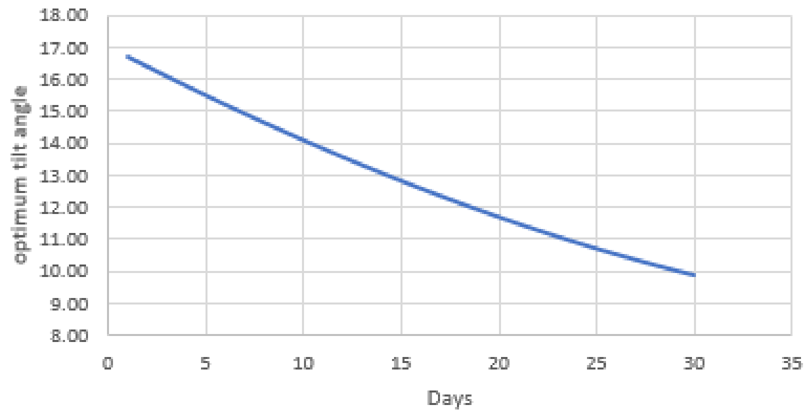

Fig. 3. *Tilt angle for May (theoretical observations)*

Difference between Theoretical and Experimental Results

Radiation Results

The rate of radiation was measured for all angles and compared with the theoretical values as shown in Figs. 4,5,6 and 7.

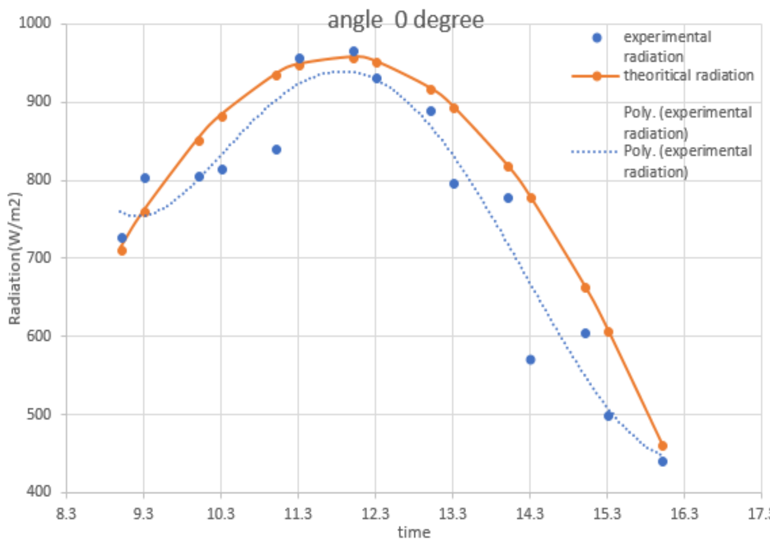

Fig. 4. *Difference between experimental and theoretical radiation at 0 degrees tilt angle*

The theoretical radiation was optimum during the mid-day and kept on reducing by time. The experimental line was also similar but with less solar radiation during most of the day except during mid-day.

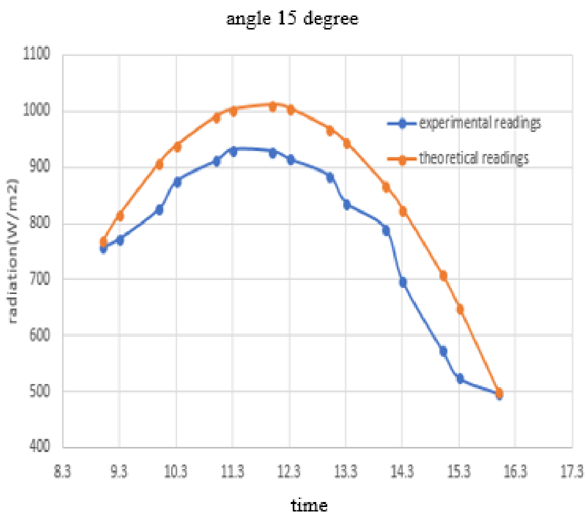

Fig. 5. *Difference between experimental and theoretical radiation at 15 degrees tilt angle*

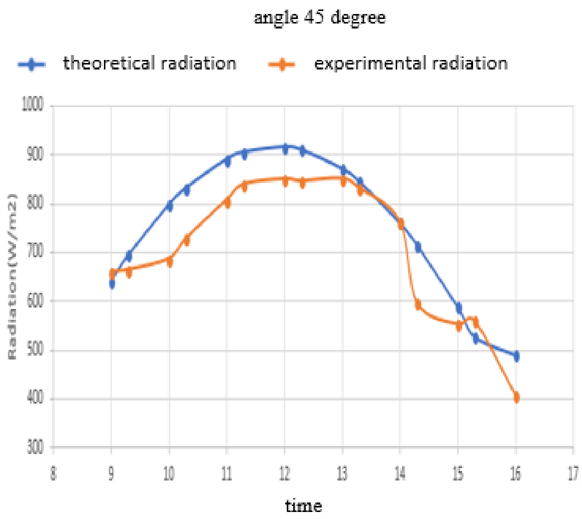

Fig. 6. *difference between experimental and theoretical radiation at 45 degrees tilt angle*

If the tilting angle was rotated to 15 degrees, the theoretical readings were quite similar to the experimental ones as shown in Fig. 5, and the 30 degrees tilt angle also yielded similar results to this one.

The 45 degrees tilting angle scored different values than the theoretical numbers as indicated in Fig. 7. According to the previous figures, the results were quite close and identical in terms of solar radiation which proves the credibility and validity of the generated results. However, it was observed that most of the experimental readings suffered from potential weather conditions such as dust. The highest solar radiation was estimated to occur at the solar time which is around 12 pm mid-day. Another measurement that was considered in the experiment was the power generated by the panel. The highest variation that was observed between the theoretical and experimental results was estimated to occur at 11 am. The differences between the generated power between the experimental and theoretical results was around 73 Watt. The following are the results of each tilt angle and the generated power:

- In 30 degrees angle the power variation was 66 Watt at 11 Am.
- In 15 degrees angle the power variation was 73 Watt at 12 Pm.
- In 45 degrees angle the power variation was 41 Watt at 10 Am.

The results have shown that the major variations between theoretical and experimental results were observed between 10 am and 12 pm due to the efficiency of the panel. It must be taken into account that the theoretical observations are taken with the optimum panel efficiency, while the experimental ones might vary according to the properties and conditions of the solar panel.

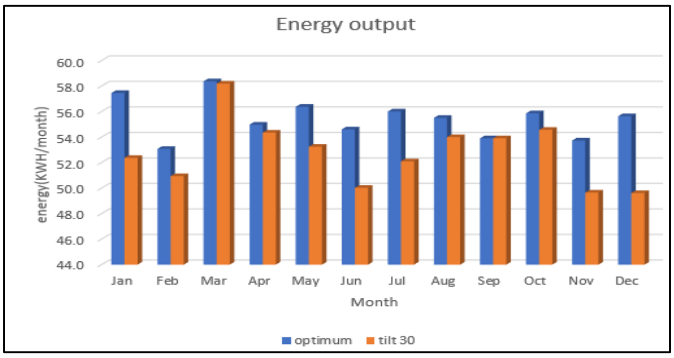

Fig. 7. *Power vs months output*

Fig. 7 demonstrates the generated power by solar panels for each month. It helps in understanding the generated power from the optimum tilt angle during the entire year. The blue bar shows the optimum energy output which keeps on changing during the year. The orange bars indicate the energy output for the solar panel if the tilt angle is set at 30 degrees. The used tilt angles for these solar panels were 50,45,34,23,13,9,11,18,30,41,50,55 respectively. The results indicated that this program can be used to determine the critical tilt angle, solar radiation, and most possible power through changing the latitude and longitude of certain points any location.

Parameters that Affect Theoretical and Experimental Results

There are multiple factors at which play a major role in introducing variations between the theoretical and experimental results such as the following:

1. Weather conditions due to the presence of clouds that covers the sun most of the day.
2. The radiation sensor is not accurately fixed in the system at which can influence the final readings.
3. The ground reflectivity factor is not quite accurate at which can generate the highest power possible.
4. Calculating the A, B, and C factors is not quite effective as it might contain any errors especially during any calculations.
5. Assuming that the rb ratio is zero when the incidence angle is higher than 90 degrees is not quite effective and can generate multiple errors.
6. The efficiency depends mainly on the solar radiation and generated power which ranged from 7.9% until 12.85% in the experimental results, while in the theoretical calculations the efficiency kept on the same value of 17.8% which is the highest efficiency possible.

Conclusion

Renewable energy is the source of electricity generation in the future and consistent research and development is required to enhance the current knowledge and understanding. One of the most common sources of renewable energy is solar panels and further studies are essential to better understand the design and efficiency of this system. Future researchers that are looking to apply the same conducted theory must take into account the results obtained in this research. It is important to take solar radiation results and measurements over a long run as it can be affected by the weather conditions or any other external factors that would prevent the generation of accurate results. Designing the solar panel to have a fixed inclined angle might help in generating more energy, and studies also recommended developing panels that can flexibly rotate during the day to generate optimum energies. The study investigated the theoretical and experimental results of power generation of solar panels in Al-Sherouk City in Egypt. The findings have shown that the theoretical and experimental results were similar, and the optimum tilting angle was determined to range between 54.7 degrees and 8.16 degrees. The study helped in providing the significance of the tilt angle for power and energy generation of solar panels. Future studies are expected to investigate similar properties in other regions and in different climate conditions.

Recommendations

There are various factors to be considered by future studies in order to develop on the findings that were reached in this study including the below:

1. Changing the tilt angle can generate the highest possible solar radiation and power, thus it must be properly applied and taken into account, but at the same time the location of the panel and weather conditions might play a major role in finding the optimum angle.
2. Ensure the consistent change of tilt angle monthly to generate the highest energy possible. These angles are 50,45,34,23,13,9,11,18,30,41,50,55 respectively in El-Sherouk City.

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