Evaluating Multiple Tilt Angles Using an Innovative Jig with a Singular PV Module

Pierre E Hertzog , Arthur J Swart

ABSTRACT--- Researchers need reliable and accurate recording instruments or systems to obtain specific data for their research. Customizable systems are not always commercially available or may be too costly. The purpose of this paper is to present an innovative jig that can be used to automatically adjust a single PV module to different tilt angles throughout the day, while simultaneously recording and storing specific data for future analysis. The analysis should provide answers as to which tilt angle enables the highest yield of output power in a particular environment. To demonstrate the operation of the designed system, voltage and current values of a 20 W PV module were recorded for nine different tilt angles and at 10-minute intervals during the solar productive period of the day. The results were evaluated, and it was found that the recorded results from the designed system correlate well with previous research resulting in its validity. It is recommended that the designed innovative jig be used to record data from a singular PV module at multiple tilt angles under various environmental conditions.

Keywords - Solar radiation, Electronic measurements, Arduino

1. INTRODUCTION

"I had many opportunities to get behind products in the past, and I was always careful to evaluate all of them. I will not put my name to shoddy items" [1]. These words, by British explorer Bear Grylls, highlight that before endorsing a specific product, it needs to be evaluated. A thorough evaluation is essential with any new invention to ensure a continuous cycle of improvement [2]. Ongoing evaluation of products or components exposed to environmental conditions is equally important due to the adverse effects of climate change. These effects include a wide range of climatic variables, not just temperature and precipitation [3].

One product that is usually influenced by ever-changing climatic conditions is a PV module [4]. Research has shown that an increase in the surface temperature of a PV module leads to a decrease in the output power. The output power may also be influenced by dust, cloud or tree cover and pigeon droppings [5, 6]. An increase in surface temperature may be attributed to climate change, to seasonal variations, and the incident angle between the incoming solar radiation and the glass surface of a PV module. The angle between the direct beam solar radiation of the sun and the normal of a PV modules' surface may be termed the incident angle, and should be less than 46° in order to enable the PV module to produce at least 15% of its rated output power [7]. In fact, optimum energy yield results when the incident is equal to 0° (the sun is directly perpendicular to the glass surface of a PV module – see Figure 1).

However, it is also at this incident angle of 0° that a PV module's surface temperature reaches its highest value, as direct infrared radiation from the sun is now also perpendicular to the surface. Infrared radiation is part of the solar spectrum that causes a PV module to heat up [8]. The more solar infrared radiation is reflected away from a surface, the less it is absorbed, and the cooler a surface will remain upon direct exposure [9]. Therefore, a compromise seems to exist between the incident angle (and thus reflection angle) and the PV module surface temperature, that both impact on the energy yield of a PV module.

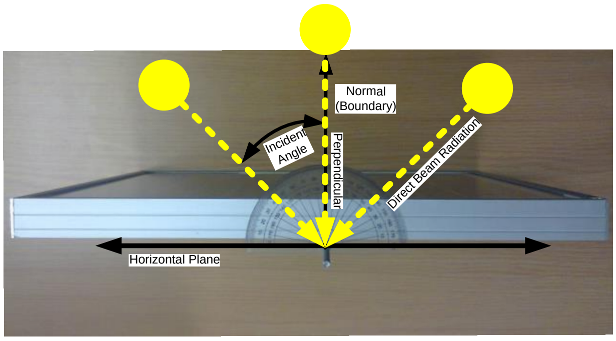

Figure 1: Incident angle shown and the direct beam radiation when perpendicular to the horizontal plane of a PV module

Repetitive testing, over an extended period, to decide which tilt angle contributes to the highest output power from a stationary PV module under changing environmental conditions would help to absolute validity [10], and establish to what degree this compromise exists. In other words, should the incident angle be exactly 0°, or maybe a little more or a little less, to enable the reflection of solar infrared radiation thereby reducing the degree to which the surface temperature rises? To answer this question requires an experimental design with a specific practical setup or innovative jig.

The objective of this work is to describe an innovative jig that can be used to automatically adjust a singular PV module to different tilt angles throughout the day, thereby establishing which one yields the highest output power for a specific environment. This innovative jig could also be used to answer the research question posed in the previous paragraph. The paper firstly discusses the selection of the tilt angles that were used. The innovative jig is then presented along with the methodology used to determine its reliability and validity. Quantitative data derived from the innovative jig is then presented using descriptive statistics.

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2. MULTIPLE TILT ANGLES

Research by Heywood and Chinnery suggest using tilt angles which are either equal to the Latitude value of the installation site, or then Latitude plus 10° or Latitude minus 10° in the southern hemisphere [11]. These three different tilt angle recommendations are according to change in season. A lower tilt angle is recommended for the summer season, whereas a higher tilt angle proposed for winter season [4]. Three fixed PV modules were used in another study to determine the effect that three different tilt angles exerted on the output power of identical modules in a semi-arid region of South Africa. These modules mount at Latitude +10°, Latitude and Latitude -10°. The period of the study spanned twelve months, and the results are shown in Figure 2 [12]. The polynomial function was used to insert a trend line onto the graph for each of the three tilt angles, and it observes that a tilt angle of Latitude +10° (φ + 10°) performed better in the winter and Latitude -10° (φ - 10°) did better in the summer. The power curves also follow the accepted annual solar radiation curve that peaks in the summer and dips in the winter. However, three identical PV systems had to be designed where shading of one PV module (caused by a pigeon or pigeon droppings [5]) would have significantly impacted on the overall results. Using a single PV module for multiple tilt angle observations overcomes this limitation.

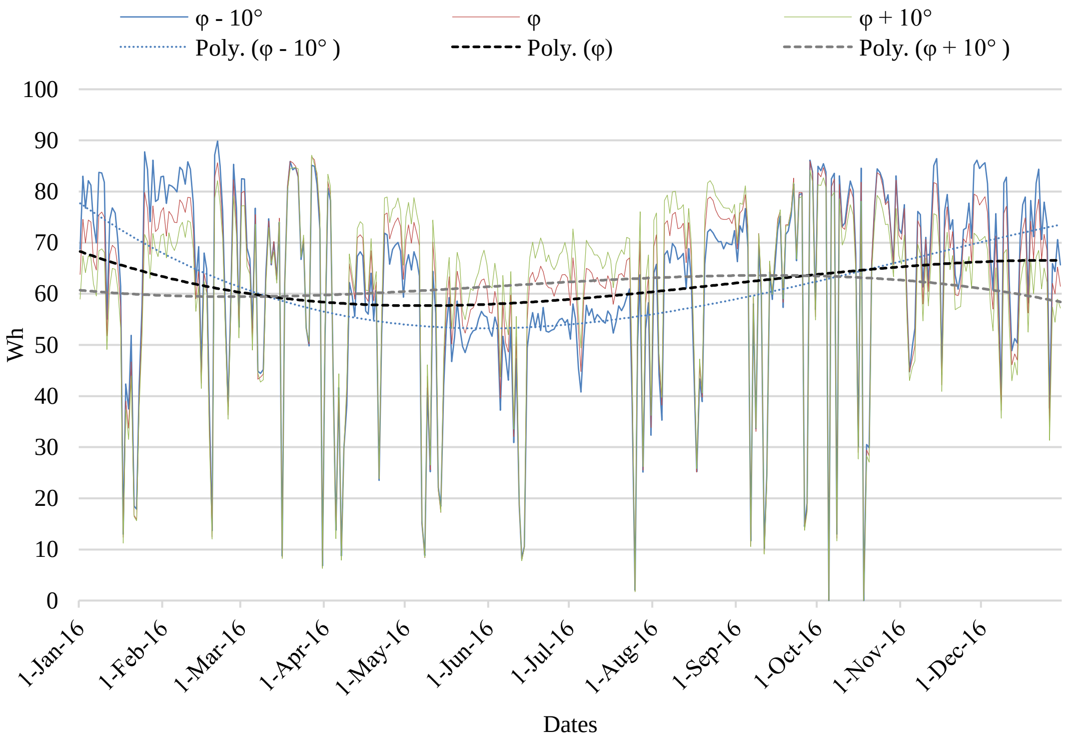

Figure 2: Average Wh per day over in 2016 [12]

A total variation of 20°, therefore, results between Latitude +10° and Latitude -10°. This 20° was multiplied by 2 to give the full range between the upper and lower limits of the multiple tilt angles that were selected for the research site in the study that is presented in this paper. This range was divided by 5 to give nine specific tilt angles to which the innovative jig would be set (see Table 1).

The research site is the Central University of Technology (CUT) that is located in the provincial capital, Bloemfontein, of the Free State province of South Africa. The Faculty of Engineering, Built Environment and Information Technology are located on the eastern side of the main campus of CUT, with several laboratories and research facilities. One such facility has a fourth-floor balcony facing northwards, with unobstructed views of the sun. This ensures that direct beam radiation of the sun is received by PV modules throughout the day, including the innovative jig that was designed for this research. The exact Latitude and Longitude coordinates of this location is 29°07'16.7"S and 26°12'58.2"E [10].

Table 1: Tilt angles used in this research

5° changes in tilt angle to reach +20° (closer alignment to the normal of Figure 1)				Research site Latitude	5° changes in tilt angle to reach –20° (closer alignment to the horizontal plane of Figure 1)			
49°	44°	39°	34°	29°	24°	19°	14°	9°

It is important to note that these different tilt angles would provide various angles of incident and reflected angles of the direct beam radiation of the sun. For example, 49° could provide a higher reflective angle than 0° at noon. However, this reflective angle would change as the sun moves across the sky from east to west. It is noteworthy that 80% of the visible wavelength of solar

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energy is absorbed by the leaves of plants for photosynthesis, while 80% of the solar infrared radiation is reflected or transmitted through the leaves [13]. This explains while the leaves of trees remain cool. However, a PV module does not allow any radiation to pass through it, as it has a solid surface onto which the PV cells are mounted. The varying reflective angles would, therefore, impact on the amount of solar radiation received by the PV module, impacting further on the surface temperature and output power yield. The compromise between incident angle (opposite of reflective angle) and tilt angle to provide the highest yield of output power could be determined using an innovative jig that is presented in next section.

3. INNOVATIVE JIG

In order to record the performance of a PV module at various tilt angles, the system in Figure 3 was developed. The system consists of several components that are detailed below. The tilt angle of a 20 W polycrystalline PV module is adjusted by using a 12 V linear actuator with a 100 mm stroke that is controlled by an Arduino microcontroller (UNO). The microcontroller controls the direction and position of the actuator, and this allows the researcher to vary the tilt angle of the module under test. Because of the relatively high current drawn by the actuator, a 5 V relay module is used for switching, as the actuator is powered from a 12 V battery. Current and voltage from the PV module are measured via an interfacing circuit. The measured data is then stored on a cloud server (Google Sheets) via a SIM800 cellular module. As the system functions independently from a mains power supply, the PV module under test is also used to charge a 12 V 7 Ah gel lead acid battery via a 20 A solar charger (ACDC CLM-20). This battery is used to power the microcontroller and other system components. During the measurement process, the solar charger is decoupled from the PV module, and four 5 W regulated LED's couples in parallel as the load. Previous research has shown that specific LED lamps are used as a suitable load for PV modules [14]. A total of nine measurements are taken in 1-minute intervals over 10 minutes. Once the measurement process is complete, the PV module is switched back to the solar charger to charge the battery.

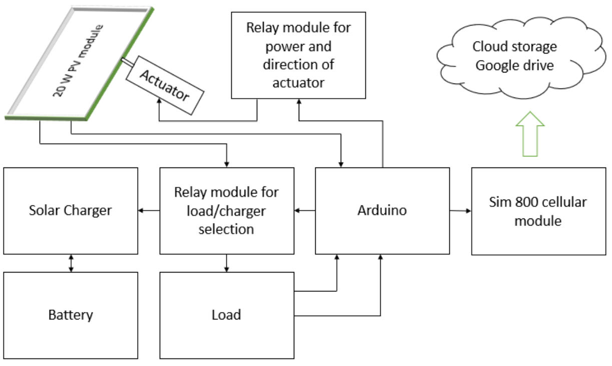

Figure 3: Block diagram of the designed system

4. METHODOLOGY

The purpose of this paper is to present an innovative jig that can be used to automatically adjust a singular PV module to different tilt angles throughout the day, thereby establishing which one yields the highest output power for specific environmental conditions. Data regarding the yield of a 20 W PV module was recorded for nine different tilt angles as sown in Table 1. As the aim of this paper focuses on the development and working of the designed jig, data are presented only for September 2018. Current and voltage measurements were taken for the nine different tilt angles during 10-minute intervals for the solar productive period of the day. During the night time, when there is no solar radiation, the system monitors the output voltage of the PV module every 10 minutes. The measurement process is set to start when the monitored PV output voltage increases above 5 V. The Arduino microcontroller then activates the actuator to extend its arm outwards, thereby increasing the tilt angle of the PV module to 49°. This requires an initial high amount of energy to be drained from the battery, with subsequent fewer amounts required as the PV module's tilt angle is decreased. This results in energy conservation, as the tilt angle does not need to be increased for each measurement (requires extending the arm of the actuator).

The solar charger is then decoupled, and the LED load is connected to the output of the PV module. Current and voltage measurements are recorded and stored in RAM. The microcontroller then activates the actuator to withdraw its arm (less energy required than extending its arm), thereby decreasing the tilt angle of the PV module by intervals of 5° until the lower limit of the range is reached as shown in Table *1*. Current and voltage measurements are recorded for each tilt angle adjustment. Once the final current and voltage measurements are made after 10 minutes, the stored data in the RAM is sent to a cloud server via the cellphone module that is connected to the microcontroller. The microcontroller then activates the actuator again to increase its arm to set the PV module to a tilt angle of Latitude. The LED lamp is disconnected, and the solar charger is reconnected so that the battery can be charged. The system remains in that state for 10 minutes at which stage the next set of measurements are initiated by the microcontroller.

5. RESULTS AND DISCUSSION OF RESULTS

Current and voltage measurements were recorded for nine different tilt angles during September 2018. Figure 4 represents the recorded data for 8 and 9 September 2018 as an example. It is evident that there was much cloud movement on 8 September (left-hand section of the figure shows several spikes), where 9 September was relatively cloud free. It can also be observed that the maximum yield is around noon, where the direct beam radiation of the sun is perpendicular to the surface of the PV module (angle of 90° where the sun is aligned to the normal of Figure 1). The maximum output power for the PV module occurred when the tilt angle was adjusted to between 39° and 29°. This correlates well with the daily solar radiation

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curve that generally peaks around noon, contributing to the validity of the obtained data. Moving from winter (June) into summer (December) also requires a tilt angle adjustment from a higher value (latitude + 10°) to a lower value (latitude minus 10°) [15].

Note how the higher tilt angles (29° and above) seem to enable the PV module to produce more output power in the morning as compared to the lower tilt angles (24° and below) while in the afternoon the trend seems to reverse after 3 pm. It seems that environmental conditions during the late afternoon enable the PV modules to perform better at lower tilt angles as compared to higher tilt angles.

Various studies have shown the negative influence of rising module surface temperatures on the performance of a PV module, and especially on its output power [16, 17]. It can further be observed that the maximum instantaneous output power of the singular 20 W PV module was higher on 8 September than on 9 September. This can be contributed to the lower module temperature on 8 September due to the overcast day, as higher ambient temperatures do lead to lower output powers. The peak value of 26.1 W that was recorded on 8 September at 12h40 may also be due to the cooler overcast period just before full solar radiation occurred. On 9 September when there was no significant cloud movement, the maximum recorded instantaneous output was 19.9 W which is 6.2 W less than the maximum of 8 September 2019.

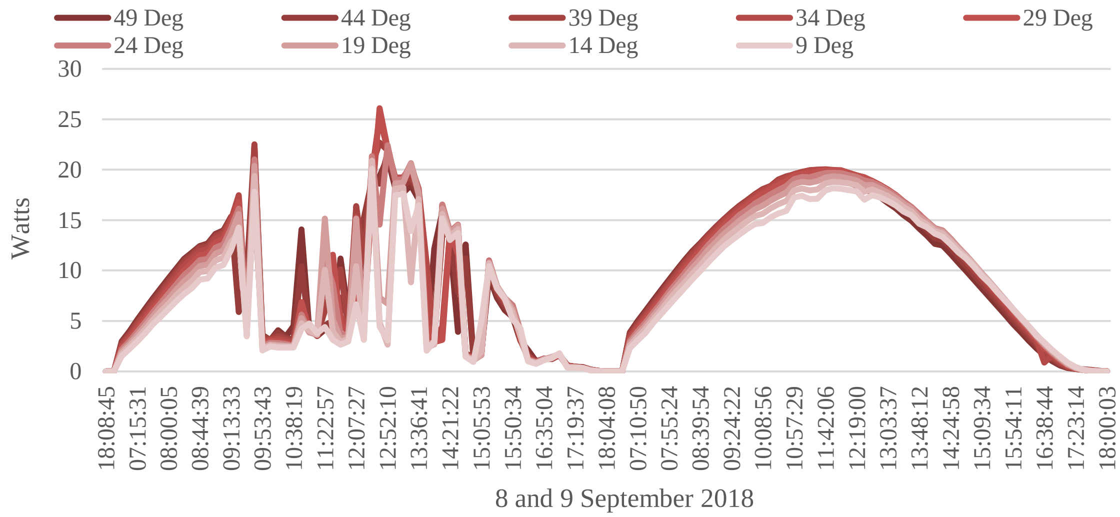

Figure 4: Output power curves of a PV module for nine different tilt angles for 8 and 9 September 2018

The month of September marks the start of spring for the research site. Data from this month correlates well with previous research from this site, where it was found that the optimum tilt angle for spring and autumn is around latitude, while in summer it is lower and in winter it is higher than latitude [12, 15, 18]. The highest average recordings for September were for a tilt angle of 34° with a value of 8.03 W (see Figure 5). This may be because September is the first month of spring where the annual solar radiation curve is still increasing from its minimum value in winter to its maximum value in summer. This also impacts on the incident angle of the direct beam radiation from the sun on the surface of the PV module. This incident angle changes continually through the year as the sun's azimuth angle and zenith change regularly as the earth orbits the sun (variation is primarily due to the tilt angle of the earth that is set at 23.5°). This result also correlates well with previous research by the authors as presented in

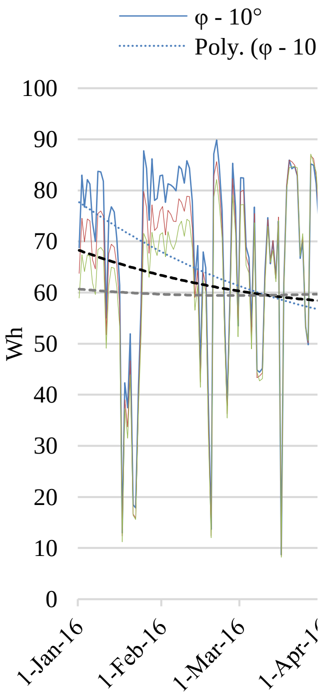

Figure 2 where it can be seen that the optimum tilt

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angle is higher than Latitude in September and only moves towards Latitude in middle October [12].

As an additional interpretation, the number of samples above 80% (16 W for the 20 W module) of the rated power of the module were counted and displayed in Figure 5. Similar results can be observed where the highest count of samples above 16 W was recorded for a tilt angle of 34°. The standard deviation is also shown that indicates a wide distribution of the output power that also adds to the validity of the data. Output powers from a few mW up to 20 W are recorded that will lead to a high standard deviation. The median indicates the centre point where half of the obtained values are above it, and the other half are below it. Given that the median is much lower than the mean, or average, suggests that there is a high percentage of outliers (several measurements where the output power is very low). This is visible on the left and right-hand side of the output power curve shown in Figure 4. In fact, for almost 4 hours of the day (06:30 until 08:30 and from 15:00 until 17:00), the output power of the PV module is less than 50% of its rated power thereby contributing to these outliers. Figure 6 shows two statistical results for the recorded data.

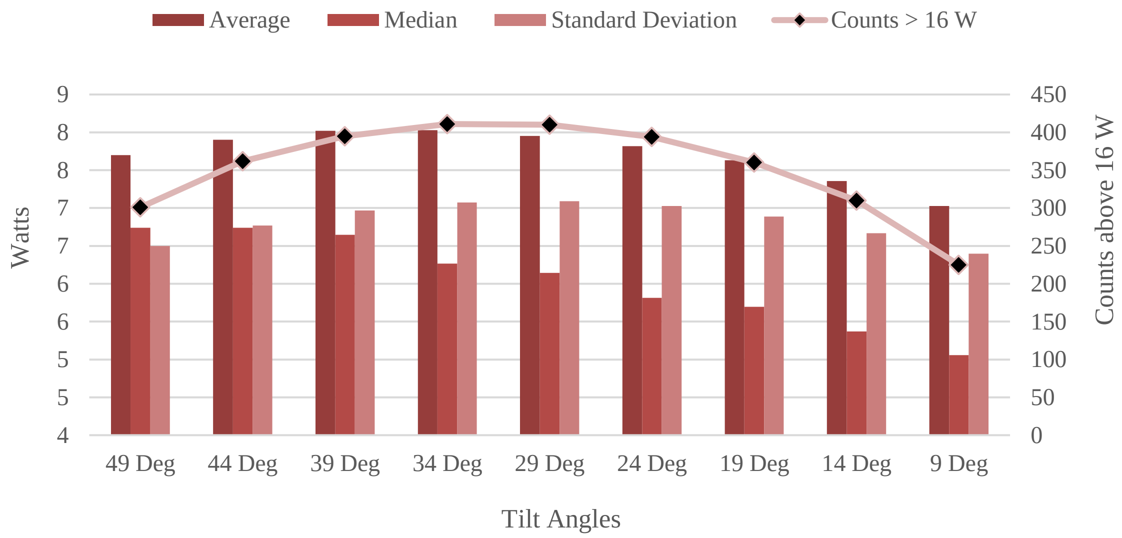

Figure 5: Descriptive statistics of nine different tilt angles for September 2018

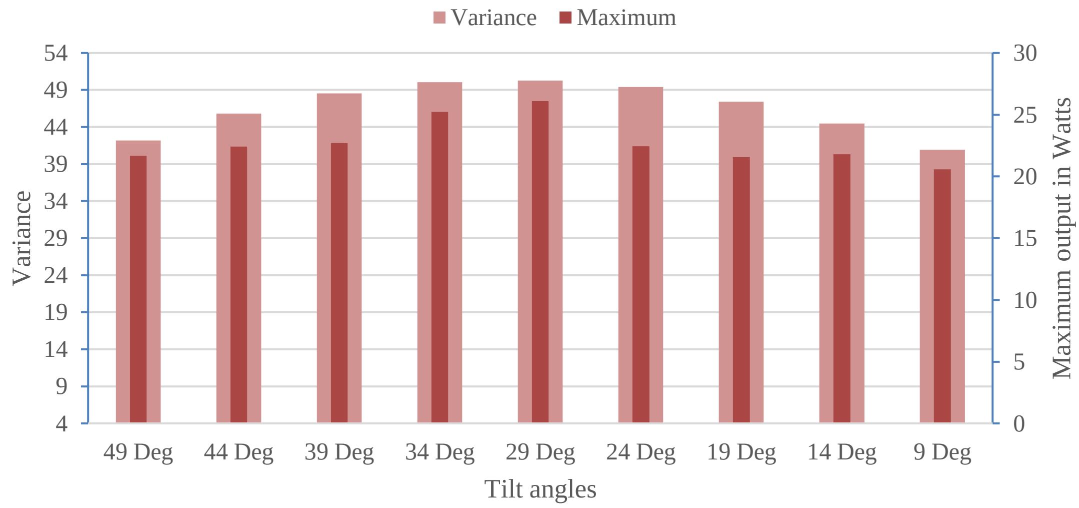

Figure 6: Maximum output power and variance values of nine different tilt angles for September 2018

The maximum instantaneous power (26.1 W) for one specific day in September was recorded for a tilt angle of 29°. As can be expected, and discussed in previous paragraphs of this section, the maximum recorded value should occur close to latitude for September that represents spring at the research site that is situated in the southern hemisphere. The variance in the range of recorded data is also presented in Figure 6. The variance values complement the standard deviation values and indicate that several values in the data set are far from the mean and each other. This relates once again to the low output power of the PV module during early morning and late afternoon.

6. CONCLUSION

The motive behind this paper is to demonstrate an innovative jig that can be used to automatically adjust a singular PV

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module to different tilt angles throughout the day, thereby establishing which one yields the highest output power for a specific environment. The innovative jig includes an automated measuring system for recording and storing current and voltage measurements for future analysis. To demonstrate the working and validity of the designed system, data were collected during September 2018. Data validity was attained by noting the similarity between the output power curve of the PV module and the daily solar radiation curve. It was further enhanced by considering that the highest output power from a PV module occurred for a tilt angle of 29° that correlates well with previous research for this site. The highest average readings for September were at a tilt angle of 34°. This may be because September is the first month of spring and following the annual solar radiation curve, the movement of the sun will require a higher tilt angle in winter and a lower tilt angle in summer. This result also correlates well with previous research, as discussed in the results section of this paper.

It can thus be concluded that the innovative jig that was developed to record the output power of a singular PV module at multiple tilt angles can be used at various research sites to obtain current and voltage measurements for different environmental conditions. This helps to minimise the variables of the research, as only one PV module is used instead of multiple PV modules, thereby contributing even further to the validity of the results.

REFERENCES

1. Brainy Quote. (2018, 19 March). *Homepage*. Available: http://www.brainyquote.com/quotes/
2. C. Lumsden and L. Byrne-Davis, "Medicine and Dentistry," *A Handbook for Teaching and Learning in Higher Education: Enhancing Academic Practice,* p. 408, 2014.
3. P. Zhang, et al. "Economic impacts of climate change on agriculture: The importance of additional climatic variables other than temperature and precipitation", Journal of Environmental Economics and Management, vol. 83, pp. 8-31, 2017.
4. P. E. Hertzog and A. J. Swart, "Determining the optimum tilt angles for PV modules in a semi-arid region of South Africa for the summer season," SATNAC 2015, Arabella, Hermanus, Western Cape, 2015.
5. P. E. Hertzog and A. J. Swart, "Detecting the presence of pigeons on PV modules in a pico-solar system " AFRICON 2017, South Africa. ISBN: 978-1-5386-2774-7, 2017.
6. A. J. Swart and P. E. Hertzog, "Quantifying the Effect of Varying Percentages of Full Uniform Shading on the Output Power of a PV Module in a Controlled Environment," SATNAC 2014, Boardwalk Conference Centre, PE, South Africa, 2014.
7. A. J. Swart and P. E. Hertzog, "Validating the acceptance zone for PV modules using a simplified measuring approach," 13th International Conference on Electrical Engineering, Electronics, Computer and Information Technology (ECTI-CON), Thailand, 2016.
8. A. H. Al-Waeli, et al. "Photovoltaic thermal PV/T systems: A review," *International Journal of Computation and Applied Sciences IJOCAAS,* vol. 2, pp. 62-67, 2017.
9. J. White and D. Montgomery, "Low-loading titanate inorganic pigments for use in infrared reflective colors," ed: Google Patents, 2015.
10. P. E. Hertzog and A. J. Swart, "Optimum tilt angles for PV modules in a semi-arid region of the southern hemisphere " *IJET, International Journal of Engineering & Technology,* vol. 7, pp. 290-297, 2018.
11. S. Armstrong and W. G. Hurley, "A new methodology to optimise solar energy extraction under cloudy conditions," *Renewable Energy,* vol. 35, pp. 780-787, 2009.
12. P. E. Hertzog and A. J. Swart, "Optimum Tilt Angles for PV Modules in a Semi-Arid Region of the Southern Hemisphere," *International Journal of Engineering & Technology,* vol. 7, pp. 290-297, 2018.
13. S. Louafi et al. "Effect of vegetation cover on thermal and visual comfort of pedestrians in urban spaces in hot and dry climate," *Nature & Technology,* p. 30B, 2017.
14. A. J. Swart and P. E. Hertzog, "LED's as viable power loads for experimental purposes relating to PV modules in pico-solar systems", *4th IEEE International Conference on Engineering Technologies and Applied Sciences (ICETAS)* 2017.
15. P. E. Hertzog and A. J. Swart, "Validating the optimum tilt angle for PV modules in a semi-arid region of South Africa for the winter season," in *ECTI-CON 2016,* Chiang Mai, Thailand, 2016.
16. T. Huld and A. M. G. Amillo, "Estimating PV module performance over large geographical regions: The role of irradiance, air temperature, wind speed and solar spectrum," *Energies,* vol. 8, pp. 5159-5181, 2015.
17. A. Makki, et. al. "Advancements in hybrid photovoltaic systems for enhanced solar cells performance," *Renewable and sustainable energy reviews,* vol. 41, pp. 658-684, 2015.
18. P. E. Hertzog and A. J. Swart, "Validating three different tilt angles for PV modules in a semi-arid region " in *International Conference on Innovative Research and Development (ICIRD) 2018,* Klong Luang, Thailand, 2018.

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