VALIDATING THE OPTIMUM TILT ANGLE FOR PV MODULES IN THE CENTRAL REGION OF SOUTH AFRICA FOR THE WINTER SEASON

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Abstract

Optimizing the output power of any PV module involves a number of factors, including the setting of the tilt angle. The purpose of this paper is to present empirical evidence validating the optimum tilt angle for PV module installations in semi-arid regions of South Africa for the winter season. The experimental setup includes three identical PV systems where the PV modules where set to different tilt angles as stipulated in the literature. Data was recorded from May to July 2015 using an Arduino board and LabVIEW software. Two power measurements were used to validate the optimum tilt angle as being Latitude plus 10º for the winter season.

Keywords: Alignment, Azimuth angle, flat surface, incident angle, tilted surface

1. INTRODUCTION

“Despite all the progress climate scientists have made in understanding the risks we run by loading the atmosphere with CO2, the world is still as addicted to fossil fuels as ever (Brainy-Quote, 2015).” These words, by Jeff Goodell, highlight the importance of reducing CO2 emissions and finding solutions to common global problems, like energy shortages. Load shedding has become a common occurrence in South Africa to deal with energy shortages, and is normally the last resort used to prevent a system-wide blackout (Chikobvu et al., 2012). It has in many cases a crippling effect on local business(Dekker et al., 2012). At present, there is no feasible method to store electrical power on a country-wide scale. The installed capacity must therefore be able to deliver peak demand (Kohler, 2014). Predictions are that these energy shortages and load shedding scenarios will increase, thereby necessitating the implementation of alternative energy sources, such as photovoltaic (PV) energy systems.

It must though be stated that PV module efficiencies still remain relatively low, with projections pointing to PV cell efficiency increases from 20% to 25% over the next five years, corresponding to a 25% output power increase (Gomes et al., 2014). This still, however, indicates that 75% of the absorbed solar energy is actually dumped by the PV module as wasted heat (Chen et al., 2011). These low efficiencies necessitate the optimum installation of PV modules according to relevant environmental and site conditions, thereby yielding the optimum amount of output power for a given period.

One of the major factors to consider in PV system installations is the tilt angle of the PV modules. 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 10º or Latitude minus 10º in the southern hemisphere (Armstrong and Hurley, 2009). The three different tilt angle recommendations are based on seasonal changes, where a lower tilt angle is recommended for summer months while higher tilt angles are recommended for winter months in the southern hemisphere. In the case of fixed mountings, there is the possibility of changing the tilt angle of PV modules for each season. According to Suri et al. a gain of 3% to 4% in energy production can be obtained by having two different seasonal tilts, changing them every 6 months (Suri et al., 2012).

However many environmental conditions influence the optimal orientation for individual locations, including cloudiness, temperature, shading, dust, rain (which washes away the dust), snow and bird droppings (Haysom et al., 2015). Research, in a pollution intensive area of South Africa, indicated that, for a stationary PV module, the tilt angle should be at Latitude plus 10º for optimum power yield throughout the year (Asowata et al., 2013). The research was conducted in an area that was declared an "airshed priority area" due to the concern of elevated pollutant concentrations within the area, being specifically particulates (Government Gazette, 2008). Would this yearly tilt angle recommendation of Latitude plus 10º hold true for other areas in South Africa, especially for semi-arid regions where excessive dust and heat are experienced?

The purpose of this paper is to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. Different solar radiation components impacting on the output power of a PV module is firstly presented. Secondly, the context of the research site is established followed by the experimental setup. The research methodology, results and conclusions complete the paper.

2. SOLAR RADIATION COMPONENTS FOR PV MODULES

PV modules receive direct (beam), diffused and reflected radiation during varying atmospheric conditions (El-Sebaii et al., 2010). Direct radiation is the component where direct line-of-sight exists between the sun and the PV module, with no interruptions such as cloud cover or tree shading. Diffused radiation is the component scattered by atmospheric constituents such as molecules, aerosols and clouds (Ramachandra and Shruthi, 2007).

Reflected radiation occurs when light energy is reflected off trees, buildings or other objects towards the PV module. Figure 1 illustrates direct, diffused and reflected radiation received by a specific PV module installed at the Central University of Technology (CUT) in Bloemfontein, Free State.

On a clear sunny day, the direct radiation component contributes about 90% to the total available solar radiation, with diffused and reflected radiation components supplying the remaining 10% (Oh et al., 2015). In the following section the research site will be placed into context.

3. CONTEXT OF THE RESEARCH SITE

South Africa has some of the best solar radiation resources in the world, where the average daily solar radiation varies between 4.5 and 7 kWh / m2 (Mulaudzi et al., 2012). In the heart of South Africa lies the Free State province with Bloemfontein as the provincial capital. The main campus of CUT is located in Bloemfontein where the Faculty of Engineering and Information Technology resides. The co-ordinates of CUT's main campus is 29°07'17.24” S (Latitude) and 26°12'56.51” E (Longitude) (Central University of Technology, 2014), and serves as the installation site for this research study. Bloemfontein is a semi-arid region (82% of South Africa is classified as such a region (Annandale et al., 2011) with a daily average global horizontal radiation of 5.15 kWh / m2 / day (Mulaudzi et al., 2012). Annual rainfall in Bloemfontein is around 550 mm (Dingaan and Du Preez, 2013) with the majority of rains falling in the summer months and water restrictions being imposed during the winter season. Localized dust storms often occur in late winter due to open pan surfaces and large agricultural lands (Wiggs and Holmes, 2011). These conditions are typical of arid and semi-arid regions, which are often characterized by water scarcity, hot dry weather, large areas of poor soils (Ramroudi and Sharafi, 2013) and dust storms (Doronzo et al., 2014). In the following section, the experimental setup that was used for collecting the quantitative data to determine the optimum tilt angle for winter months at the CUT in Bloemfontein is presented.

Fig. 1: Different radiation beams impacting on a PV module

4. EXPERIMENTAL SETUP

The experimental setup consists of three identical PV systems, each comprising a 10W polycrystalline PV module, a 5A solar charger, a 20Ah battery and a 5W LED load (see Figure 2 for the main block components). All three systems are interfaced with an Arduino board (controlled by LabVIEW software) using a singular data logging interface circuit. This circuit has been reported on by a number of researchers (Ozemoya et al., 2014, Schoeman et al., 2013, Swart et al., 2013) and provides power conditioning between the PV system and the data logging system (Arduino and LabVIEW).

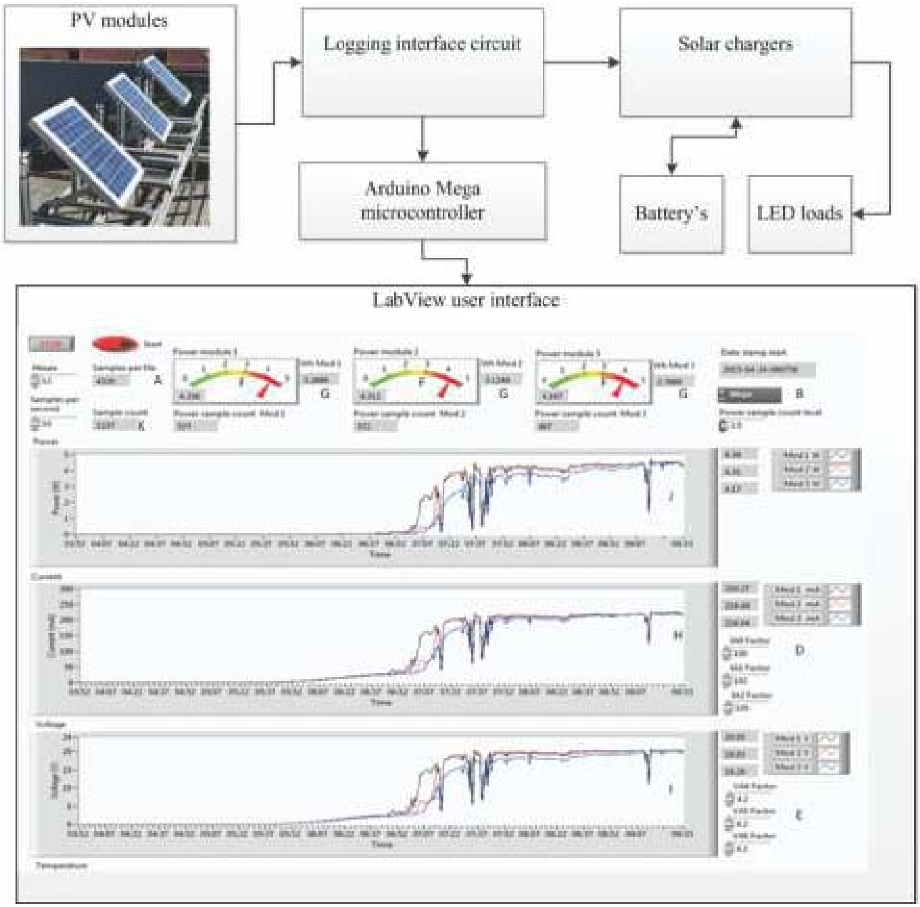


Fig. 2: Experimental setup

The three PV modules were mounted onto an aluminum frame and initially set to the same tilt angle equal to the Latitude of the installation site. The output power of these modules was then recorded and analyzed over a four week period (October 2014), resulting in a coefficient of variation of 1.4%. This coefficient of variation is calculated using the standard deviation and mean of the collected data. This was done to calibrate all three systems to a standard reference, thereby ensuring the validity and reliability of all subsequent measurements. The modules of the identical PV systems were then set to three different tilt angles as listed in Table 1, based on previous research. Reasons for using the LabVIEW software in conjunction with an Arduino board are substantiated in the following sections.

Table 1: Three different tilt angles based on research done by Heywood (Heywood, 1971) and Chinnery (Chinnery, 1981)

Author	**Equations of latitude**	**Tilt angle for Bloemfontein**	**Time period used**
Heywood	$\varphi - 10°$	$29° - 10° = 19°$	Summer
Heywood	φ	$29°$	Autumn / Spring
Chinnery	$\varphi + 10°$	$29° + 10° = 39°$	Winter

4.1 LabVIEW

National Instruments LabVIEW is a graphical programming language that has its roots in automation control and data acquisition. It's graphical representation, similar to a process flow diagram, was created to provide an intuitive programming environment for scientists and engineers. The language has matured over the past 20 years to become a general purpose programming environment. LabVIEW has several key features which make it a good choice in an automation environment. These include simple network communication, turnkey implementation of common communication protocols (RS232, GPIB, etc.), powerful toolsets for process control and data fitting, fast and easy user interface construction, and an efficient code execution environment (Elliott et al., 2007).

4.2 Arduino bord

The Arduino is an electronic platform designed to simplify the process of studying digital electronics (Hertzog and Swart, 2015) and consists of a microcontroller, a programming language and an Integrated Development Environment (IDE) (Martins et al., 2013). Arduino was born to teach Interaction Design, a design discipline that puts prototyping at the centre of its methodology (Banzi, 2009). The designers attempted to design a user-friendly software and hardware interface, making freely available the necessary documentation to support it (Buechley and Eisenberg, 2008).

4.3 Measurements

Voltage readings are obtained from the Arduino board by using the analog read function in LabVIEW. The obtained values are then multiplied by a predetermined factor obtained by the calibration process in order to compensate for any interface losses. The immediate value is displayed on the front panel of the LabVIEW software. This value is then filtered by a Butterworth Filter to eliminate high frequency components originating from the Arduino's analog read circuit or from the data logging interface circuit, before being written into a matrix.

Voltage readings from the Arduino board represent PV module output voltages, currents and surface temperatures. Current readings are obtained by measuring the voltage across a low value precision resistor (10Ω 10W 1%). Voltage readings are obtained by using a standard voltage divider circuit (147kΩ resistor in series with a 100kΩ resistor). Temperature readings are obtained by using a thermistor which is connected to the back of the PV module.

One way of comparing the performance of the three PV systems is to record the amount of samples where the output power of each module exceeds a set limit (3.5 W in this research). In order to record the percentage of time that each PV module produces more than 3.5 W of power, a shift register is used in which the value is incremented each time a sample's value is above the set limit. The accumulation of these values is automatically written into a singular file at the end of each day.

A second way of evaluating the performance of each of the three PV systems is to record the Watt hours (Wh) generated by each module for each specific day. This is done by calculating the mean power for a specific number of samples and then multiplying that mean power with the time in hours represented by those samples. This results in an instantaneous Wh value for a specific number of samples taken within a 24 hour period. The LabVIEW user interface is shown in the experimental setup in Figure 2, where the following is discernible (Hertzog and Swart, 2015):

- the total amount of samples that are to be recorded and written to a single file (see A);
- the Arduino board that is used for the sampling (see B);
- the set limit for the power sample count (see C);
- the calibration factor for the current (see D) and voltage of each module (see E);
- the instantaneous power for each module (see F);
- the accumulated Wh for each module (see G),
- a limited logged history as well as the instantaneous values of the current (see H), voltage (see I) and power (see J); and
- the total sample count which has been completed (see K).

5. RESEARCH METHODOLOGY

The purpose of this research is to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. An experimental research design is used where all three PV modules were initially set to the same tilt angle of 29º (Latitude value of the installation site). Four weeks of data (October 2014) was recorded to observe any significant differences between the three systems, thereby enabling calibration to a standard reference. A coefficient of variation of 1.4% was calculated indicating that all three systems were performing equally well.

The PV modules were then set to three different tilt angles, resulting in only one different variable (See Figure 3). All three PV systems were equally exposed to all other relevant variables (environmental conditions, orientation angles, charge controllers, battery's etc). Data was recorded from May to July of 2015 which corresponds to the winter season for the installation site. Power sample counts above 3.5 W and Wh results were used to determine which tilt angles yielded the highest output power for this period. PV surface temperatures were also recorded with the data depicted in figures and tables in the next section.

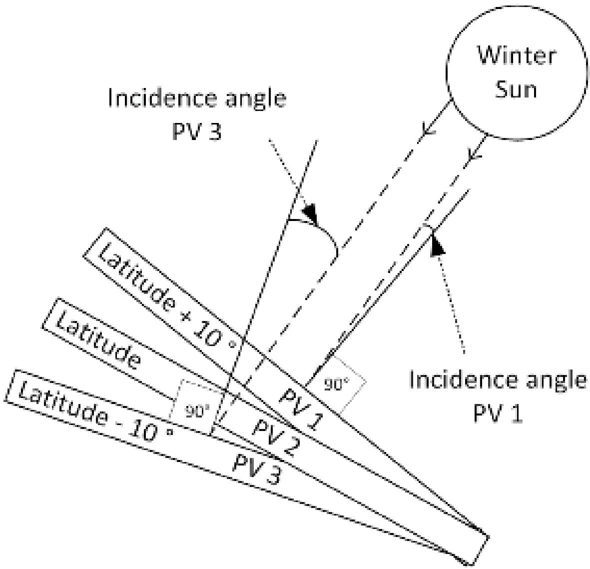


Fig. 3: PV module setup for May to July 2015 with incidence angle for PV 1 and PV 3 indicated

6. RESULTS AND DISCUSSION

Two measurements, namely the amount of power samples above 3.5 W and Wh per day were used to validate the optimum tilt angle of the PV modules.

Figure 4 depicts the number of power samples above 3.5 W for July 2015. It is evident that the sample count for PV 1 (tilt angle of Latitude plus 10º) is generally higher than that for PV 2 (tilt angle of Latitude) and PV 3 (tilt angle of Latitude minus 10º). All three PV modules follow the same trend, showing the influence of the other variables (including the environmental and climate conditions) on their output power. A graph was obtained for each of the three months after which the average monthly values were calculated and used to produce Figure 5.

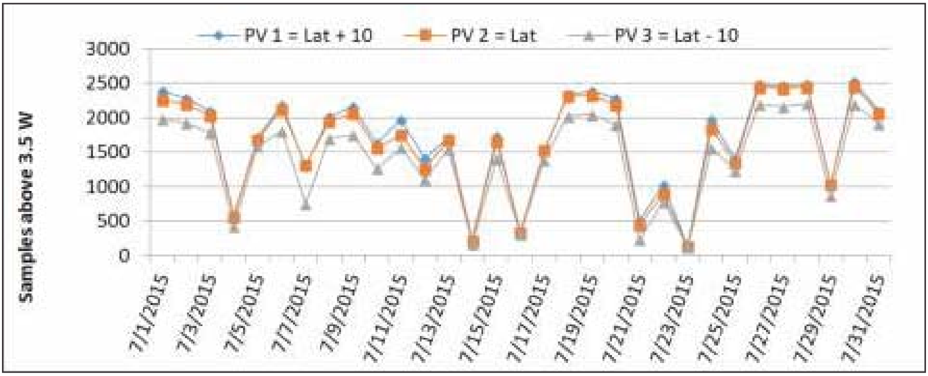


Fig. 4: Power samples above 3.5 W for July 2015

Figure 5 validates the Latitude plus 10° tilt angle (PV 1) as yielding the highest amount of output power with regard to the sample count above 3.5 W. Its average value count of 1976 is more than 200 counts higher than the Latitude minus 10° count (1745). Noteworthy is that all three counts were very similar during May 2015, thereby indicating that the sun's direct radiation component influenced all three systems to roughly the same degree. These results are further verified by the Wh measurements displayed in Figure 6, where PV 1 produced 70Wh on the 18 of July 2015, as compared to the 59Wh produced by PV 3. This can be attributed to the small incident angle of the winter sun on PV1, as compared to PV 3 (see Figure 3 in the previous section).

Fig. 5: Average power samples above 3.5 W for the three PV modules

The daily values for the Wh measurements in July are shown in Fig. 6 and the monthly averages in Fig. 7 which again validates the Latitude plus 10º tilt angle as yielding the highest output power for this period. PV 1's average output power (63Wh) is more than 6Wh higher than PV 3 (56Wh), set to the Latitude minus 10º tilt angle. The correlation between the samples above 3.5W and the Wh for July 2015 was done with the use of the Pearson Correlation equation. As can be seen in Table 2, there is a strong correlation of 0.88 for all three modules for the July period. Therefore, it can be concluded that the simplified method of counting the number of samples above a specific Wh is valid for determining the maximum output power for a given PV module.

Table 2: Correlation between the values of samples above 3.5W and Wh for July 2015

PV module and tilt angle	Correlation of samples above 3.5W and Wh
PV1 tilt angle of latitude plus 10º	0.92
PV 2 tilt angle of latitude	0.86
PV 3 tilt angle of latitude minus 10º	0.86
Average of all 3 modules	0.88

The path of the sun from east to west is shorter during the winter season in the southern hemisphere, with a corresponding lower elevation angle. This implies that a PV module with a higher tilt angle will receive more direct radiation, subsequently generating more heat that needs to be dissipated to the environment. Figure 8 validate this implication in terms of the PV module's surface temperature for July 2015. PV 1 (tilt angle equal to Latitude plus 10º) had the highest recorded value of 46ºC on the 6 July 2015.

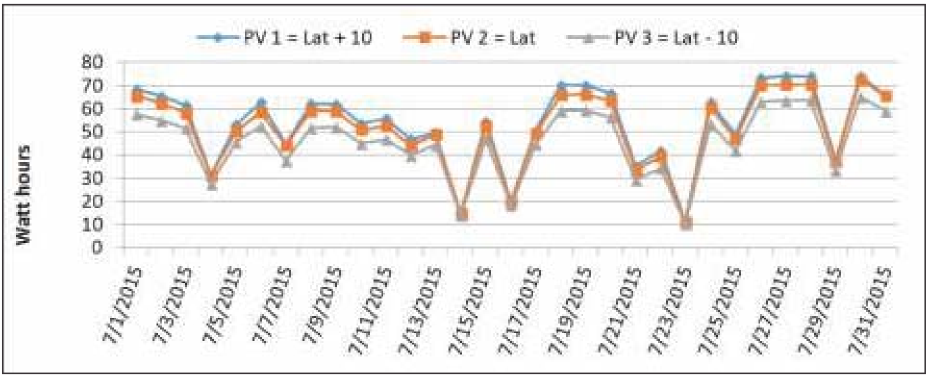
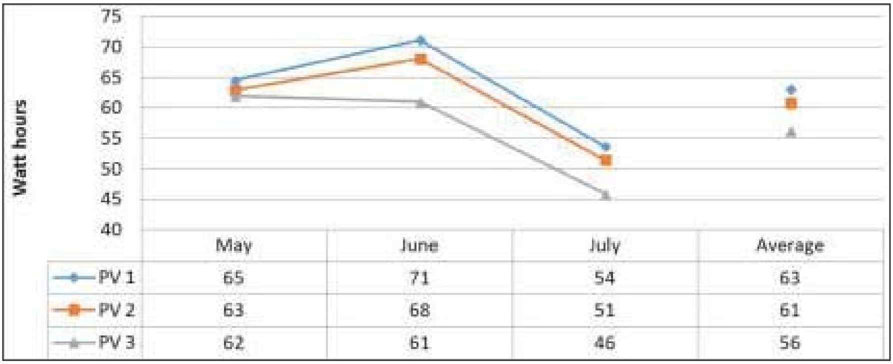


Fig. 6: Wh measurements for July 2015



	May	June	July	Average
PV 1	65	71	54	63
PV 2	63	68	51	61
PV 3	62	61	46	56

Fig. 7: Average Wh measurements for the three PV modules

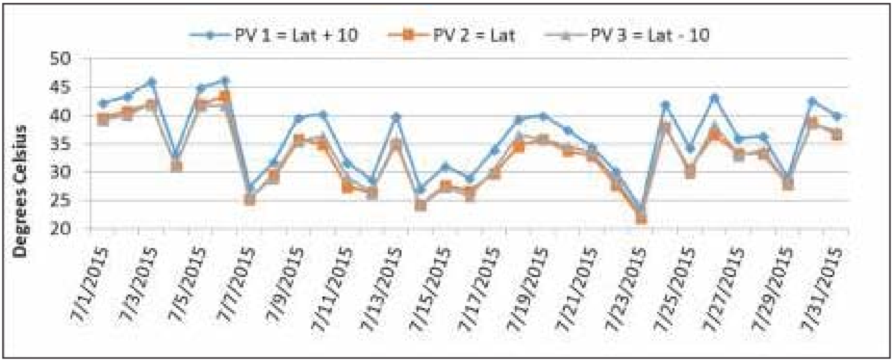
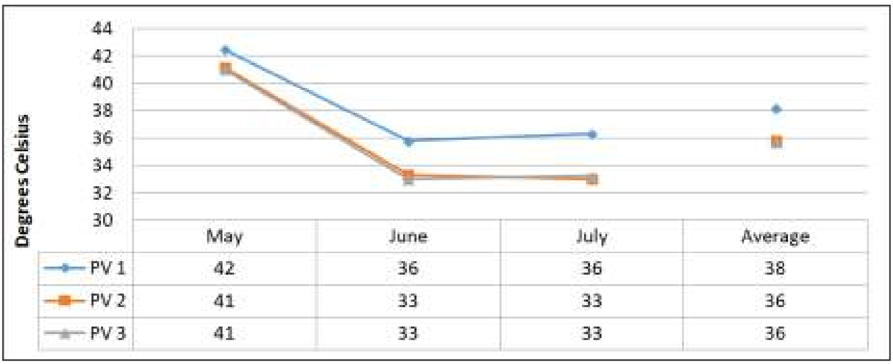


Fig. 8: Surface temperatures for the three PV modules in July 2015

The maximum surface temperature for PV 1 was higher than that for PV 3 during May, June and July (see Figure 9). These temperature results confirm earlier work done on controlling the surface temperature of PV modules to ensure higher output powers (Ozemoya et al., 2013).



	May	June	July	Average
PV 1	42	36	36	38
PV 2	41	33	33	36
PV 3	41	33	33	36

Fig. 9. Average surface temperatures for the three PV modules

7. CONCLUSIONS

The purpose of this paper was to present empirical evidence validating the optimum tilt angle for PV modules in a semi-arid region of South Africa during the winter season. Three identical PV systems were installed at CUT in Bloemfontein were specific data was collected over a three month period. Electronic measurement reliability and validity was firstly established by having all three systems set to the same tilt angle, thereby providing a standard of reference for calibration. A coefficient of variation of 1.4% was established indicating a high level of similarity between the three systems. Three different tilt angles were then used, with PV 1 being set to Latitude plus 10º, PV 2 to Latitude and PV 3 to Latitude minus 10º. Results from the power sample count above 3.5 W and from the Wh calculations indicate that PV 1 produced the highest output power for the months of May 2015 through July 2015.

Based on these results, it is recommended that PV modules be placed at a tilt angle of Latitude plus 10º for semi-arid regions in South Africa during the winter season. This is in contrast to PV module installations for pollution intensive areas (Asowata et al., 2013). A possible limitation of this study includes the fact that only one research installation site was used over a 3 month period. Making use of a time-lag study and obtaining another set of electronic measurements will serve to validate these results. Moreover, it will further help to establish what the overall yearly optimum tilt angle should be for semi-arid regions in South Africa.

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