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Analyzing the Performance of Identical PV Modules in a Semi-Arid Region over a 2-year Period

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Abstract

It is assumed that similar PV modules are expected to perform equally well under the same atmospheric conditions, especially with regard to their rated output power. However, this is not always the case due to a number of factors, which include cell degradation overtime and cell manufacturing. It has been reported that PV modules within arrays need to be identical. This is required to have equal currents flow through the branches of an array in order to prevent power mismatches, hot spots and a lower overall output power. The purpose of this paper is to analyze the performance of three identical 10 W PV modules which were used over a 2-year period in a semi-arid region, in order to identify any anomalies. An experimental research design is employed where three identical 10 W PV modules were each connected to its own power loads that were to extract more than 90% of the rated power of the module over a 2-year period. A data logging circuit is included that provides power conditioning between the PV modules and an Arduino UNO board, which serves as the data logger. This logger relays the measured data to LabVIEW where the processing, display and recording is done. Two key anomalies that were identified relate to the abnormal degradation in output power of one of the modules and the abnormal improvement in output power when a newly manufactured module is introduced into the system.

Keywords: Arduino, LabVIEW, metrology, LED, degradation.

Introduction

"Time doesn't change, time reveals." This Arabian proverb well illustrates that the passing of time reveals all. In fact, a well-known English proverb says, "time will tell." Of course, time cannot talk, but instead reveals certain attitudes, outcomes and answers to specific questions. For example, research has shown that photovoltaic (PV) modules tend to degrade by approximately 1.2% per year (Bartolo & Yousif, 2017). This required time to prove. In fact, all research requires time to reveal the answers or solutions to research questions or problems. One problem associated with PV research is the lack of abundant empirical data regarding the practical application of PV modules in different atmospheric environments. In fact, the International Solar Energy Society has, as its purpose, the encouragement of basic and applied solar research, the promotion of science and technology relating to the application of solar energy and the compilation and dissemination of research relating to all aspects of solar energy (Cox, 2013).

Basic and applied PV research must continue, and be reported on, in an effort to contribute to the scientific body of knowledge which may lead to an improved understanding of PV technologies with the ultimate goal of improving the manufacturing process. This is what the majority of literature has focused on during the past decade with regard to PV research. The rationale has really been limited to two aspects, namely the optimization of Silicon and the discovery of new materials which may be used in the manufacturing process (Sun, 2013). However, this paper is limited only to the application of PV modules in a given atmospheric environment, so as to try to better understand its operation and performance.

Recent publications have focused on the performance of PV modules under uniform shading conditions (Arthur James Swart & Pierre E. Hertzog, 2016), on the operation of LED's as viable power loads for PV modules (Swart & Hertzog, 2017) and on the importance of the tilt angle for optimum performance of stationary PV modules (Swart, 2017). These publications fall under the basic and applied research category, which is required for producing explicit knowledge (Edwards, 2001). This knowledge may help to either develop new products or to improve the features of existing products in response to fluctuating markets and industry trends (Bosua & Venkitachalam, 2013).

The purpose of this paper is to analyze the performance of three identical 10 W PV modules in a semi-arid region over a 2-year period, using empirical data, in order to identify any anomalies that may contribute to a better understanding of these modules. The target location is in the middle of South Africa, which is in the Southern Hemisphere. This is a semi-arid region with day-time temperatures well beyond 40°C in the summer months. The paper firstly discusses PV cell manufacturing and energy provision. The practical setup and methodology is then presented. Descriptive results follow with succinct conclusions.

PV cell manufacturing and characteristics

The majority of PV cells are manufactured from wafers of crystallized Silicon or more recently, thin film amorphous Silicon (Holstein, 2015). The basic manufacturing process is shown in Figure 1, where the raw material Silicon is formed into a large ingot. These ingots are usually formed by cooling molten Silicon into a form (usually a cube), after which it is cut into substrates having a thickness of several hundred micrometers (usually called wafers). Three general methods are used to make these ingots; (1) pulling an ingot from a melt (e.g. using the Czochralski process); (2) solidifying a melt in a crucible by directional solidification techniques; or (3) pouring a melt from a crucible into a mold using casting techniques (Cortellini et al., 2014). The cutting of ingots is typically performed by a wire cutter and results in a rough surface on the silicon face (Lee & Yeo, 2017). Metal contacts are added to enable electron flow. A glass substrate and protective film are added to prevent moisture infiltration. An aluminum frame is finally added to provide support that enables installation.

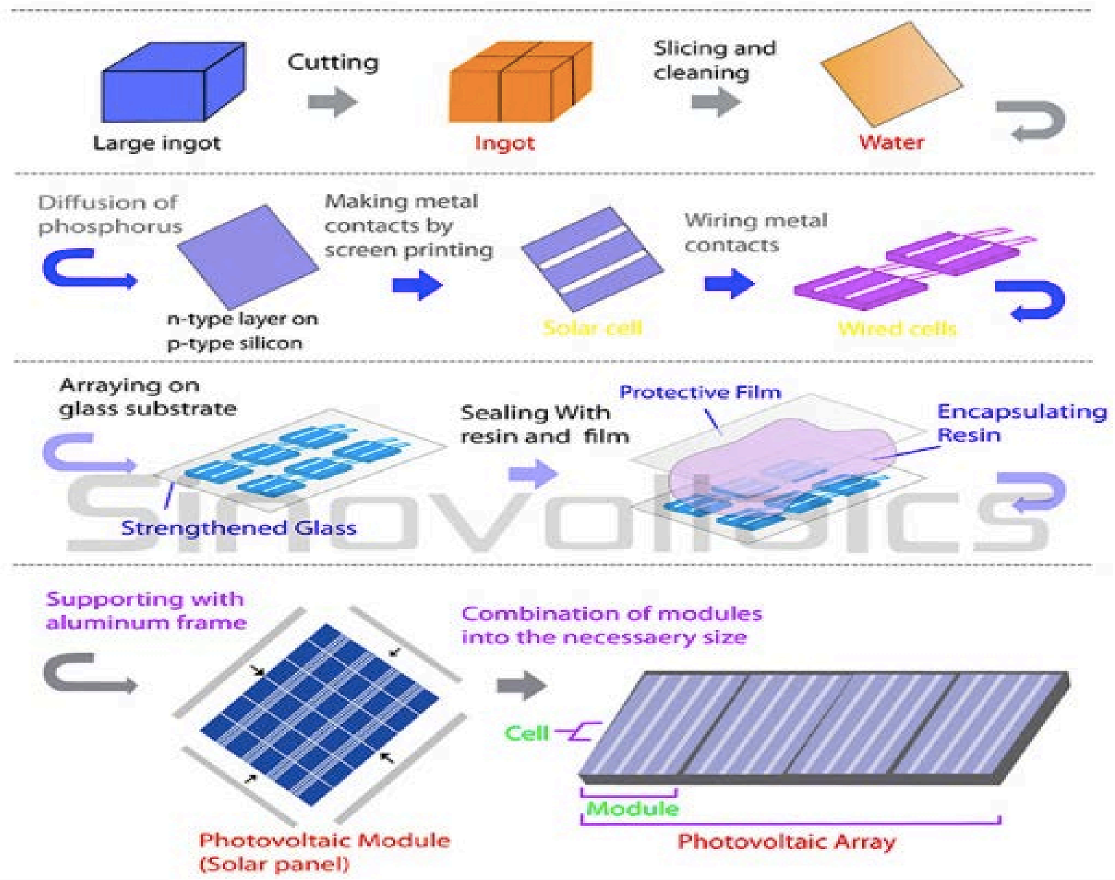


Figure 1 - PV Cell manufacturing process (SINOVoltaics.com, 2017)

Different manufacturing methods are used to achieve different efficiencies, which have an impact on the cost and size of the PV cell (Table 1 presents a concise summary of the major types used today). Mono-crystalline and poly-crystalline PV cells still dominate the market, primarily due to their higher efficiencies. After the initial manufacturing process, single cells are tested for their power output and binned with similar cells (Kim & Krein, 2013). PV cell manufacturing is not an uniform process, with output cell power generally falling over a given distribution (Kim et al., 2015).

A key requirement for PV system, is that all PV cells, or modules, need to be roughly identical (Lorenzo et al., 2014). Mismatch power losses arise when PV cells or modules with different current–voltage characteristics are connected (Massi Pavan et al., 2014). Differences arise from the unavoidable fabrication spread or from non-uniform irradiance or working temperature within an array (Luque & Hegedus, 2011).

This fabrication spread arises in the manufacturing process, which produces PV cells with relatively large tolerances in their power output capability. Industry has been able to reduce these tolerances to around 3% by using specific techniques (Ancuta & Cepisca, 2011). However, notable differences still exist in the electrical characteristics of nominally identical PV cells or modules (Massi Pavan et al., 2014).

It is well documented that PV cells degrade from extreme temperatures, UV exposure, and mechanical damage. Long-term UV exposure or cycling temperatures can lead to the internal resistance of the cell increasing due to infiltration of contaminants, such as moisture. Elevated temperatures can also lead to a decrease in shunt resistance, or resistance of the path to ground, when metal ions migrate through the cell. Furthermore, the module's anti-reflective coating (protective film) can deteriorate due to heat, UV exposure, and exposure to contaminants. Degradation resulting from mechanical damage typically results from poorly installed PV cells that are stressed by wind loads or are in a place where objects are contacting them (Bartolo & Yousif, 2017). All of these factors can lead to a PV cell degrading, resulting in decreased power output.

Table 1 - PV Module parameters (adapted from (Holstein, 2015))

PV Cell	**Type**	**R&D Efficiency**	**Commercial Efficiency**	**Market Share**
sc-SI	Silicon mono-crystalline wafer	25%	13-20%	42.2%
mc-SI	Silicon multi-crystalline / polycrystalline wafer	20.3%	11-15%	45.2%
ribbon-SI	Silicon ribbon multi-crystalline wafer		11%	2.2%
Heterojunction c-SI	Crystalline silicon wafer layered by a-SI	23%	18+ %	5.2%
a-SI	Thin film, amorphous silicon	10.1%	6-9%	4.2%
Multi-junction a-SI	Thin film, a-SI with alloy materials	12-13%		
CdTe	Thin film, cadmium telluride	16.5-16.7%	10-11%	
CIS	Thin film, copper indium disulfide		8.6-10%	
CIGS	Thin film, copper indium gallium disulfide/diselenide	19.9-20.1%	13.1%	

Each individual PV cell has an internal resistance that depends on various parameters, which include cell's physical structure, metal connectors and overall construction. As the PV cells degrade, this internal resistance usually increases, with increased thermal loss being shown (Adcock, 2016). This may further cause less current to flow, impacting on the overall output power of the cell. This effect can be magnified if multiple PV modules, or cells, are wired in series because, similar to shading effects, if one module has a higher degradation rate than other modules in the same string, then it will affect the entire string (Poissant, 2017).

Hot spots generally occur when a large number of series connected PV cells are dissipating power in a shaded cell. This results in the individual PV cells, or modules, being forced to operate at a power level other than their own, which leads to losses in overall output power (Larsen & Lindquist, 2014). These hot spots are problematic in PV systems that further accelerate cell degradation and lower system performance (Kim & Krein, 2013). They mainly occur during the day when ambient temperatures are above the STC level when the maximum power current is being drawn.

PV modules convert a certain amount of solar radiation into electrical energy, while the rest is converted into heat energy, leading to a significant rise in a PV module's temperature. This elevated temperature deteriorates the power output and induces structural degradation, resulting in a reduced PV lifespan. It has been shown that PV cells degrade faster in hot climates due to long-term thermal ageing caused by their elevated operating temperatures (Kurtz et al., 2011). Additionally, PV modules lose structural integrity due to delamination that is caused by prolonged operation under elevated temperatures (Saly et al., 2001). By studying the physical mechanisms by which PV cells degrade, design modifications can be implemented to create longer lasting PV modules (Mathews et al., 2014).

Multiple PV cells are generally interconnected to increase current flow and output voltage in a singular PV module. Similarly, multiple PV modules are interconnected to increase the overall output power from a PV array. These types of arrays are often installed on the roofs of residential homes, giving rise to the term PV roof-installation. These installations have flourished over the past few years (Swart, 2016), as many seek to minimize their dependence on the national gird, by-pass the effects of load shedding and reduce their electrical bills.

Provision of electrical energy

The national grid has continued to grow globally over the past few decades, with more and more communities being afforded the privilege of having electricity. For example, since 1991, ESKOM (national energy utility in South Africa) has connected over 4.2 million homes to the national grid, largely on a prepaid metering system, and it has provided non-grid access to 38,000 others (Albert et al., 2014). This non-grid access would primarily occur by using renewable energy systems, such as PV systems and wind turbine systems. However, connection to the national grid has two major disadvantages, that being load shedding and increased electrical energy costs.

Load shedding is defined as the set of controls, which results in a decrease of load demand in the power system in order to achieve a new equilibrium state (Reddy, 2017). Load shedding occurred regularly between 2013 and 2015 in South Africa, with many parts of the country experiencing no power for up to 2 hours per day. This enabled the system to achieve equilibrium, as specific neighborhoods where deliberately disconnected from the national grid while other remained connected. This created more problems for consumers, especially in terms of small and medium enterprises that were dependent on electrical energy to maintain their cold storage and power their electronic registers. In fact, load-shedding has caused significant damage to national economies of many countries, and even the closure of some industries in Pakistan, resulting in loss of production and jobs (Mirza et al., 2015). A similar detrimental result of load shedding has been observed in South Africa.

Electrical costs have continued to increase worldwide. For example, energy costs have risen steadily for the last 12 years in the United States, and will continue to do so for the next 20–25 years (Deb, 2014). This has also been experienced in South Africa. For example, the National Energy Regulator of South Africa (NERSA) has, since 2008, granted ESKOM an annual average increase of about 22% per annum in tariffs (Parsons et al., 2015). Recently, NERSA approved an average price increase of approximately 13% for the year 2015–2016 (Gupta & Inglesi-Lotz, 2016), with more increases planned for the future.

To negate the effects of load shedding and electrical energy cost increases, small and medium enterprises and residential homeowners need to look to renewable energy sources, including micro-solar (10 – 10 kW) and pico-solar (< 10 W) off-gird PV systems. Obtaining a deeper understanding of how PV modules in these systems perform within various atmospheric environments may help to further understand its performance and promote its adoption.

Practical setup

The practical setup consists of three identical PV systems comprising 10 W poly-crystalline PV modules (short circuit current of 0.78 A and an open circuit voltage of 20.8 V), a data logging interface circuit, an Arduino UNO board and LabVIEW software (see Figure 2). This may be classified as a pico-solar system, as the output power is lower than 10 W (Cuciureanu et al., 2016). Three different power loads (resistor, LED lamp and solar controller) where connected to the modules for a period of 15 months (starting 17 Feb 2017), in order to validate the use of a regulated LED lamp as a viable power load for such modules (A.J. Swart & P.E. Hertzog, 2016). The resistor and LED lamps were swapped around on 8 May 2017, in order to validate the performance of the power loads and not the performance of the PV module. The solar controller was consistently connected to PV3 for the entire time period (17 February 2017 to 21 August 2017). On 22 August 2017, all three PV modules were connected to identical LED lamps, in order to validate any significant differences between the modules which may have arisen over the previous 18 months (the initial PV modules used in this research are identical and were purchased from one batch and manufacturer in 2014).

Previous research has shown that a solar controller with its battery and associated load outperformed a LED lamp during the summer season for the same research site (A.J. Swart & P.E. Hertzog, 2016). In fact, the solar controller extracted 3.9% more energy from the PV module as compared to the LED lamp. A second set of confirmatory results further established the reliability and validity of the electronic measuring process and methodology (Swart & Hertzog, 2017). The results indicated, that during the winter season, the regulated LED lamps outperformed the solar controller by extracting, on average, 1.5% more power from its PV module. During this time of the research, all the PV modules were producing more than 90% of their rated output power, depending on the load condition which was being used.

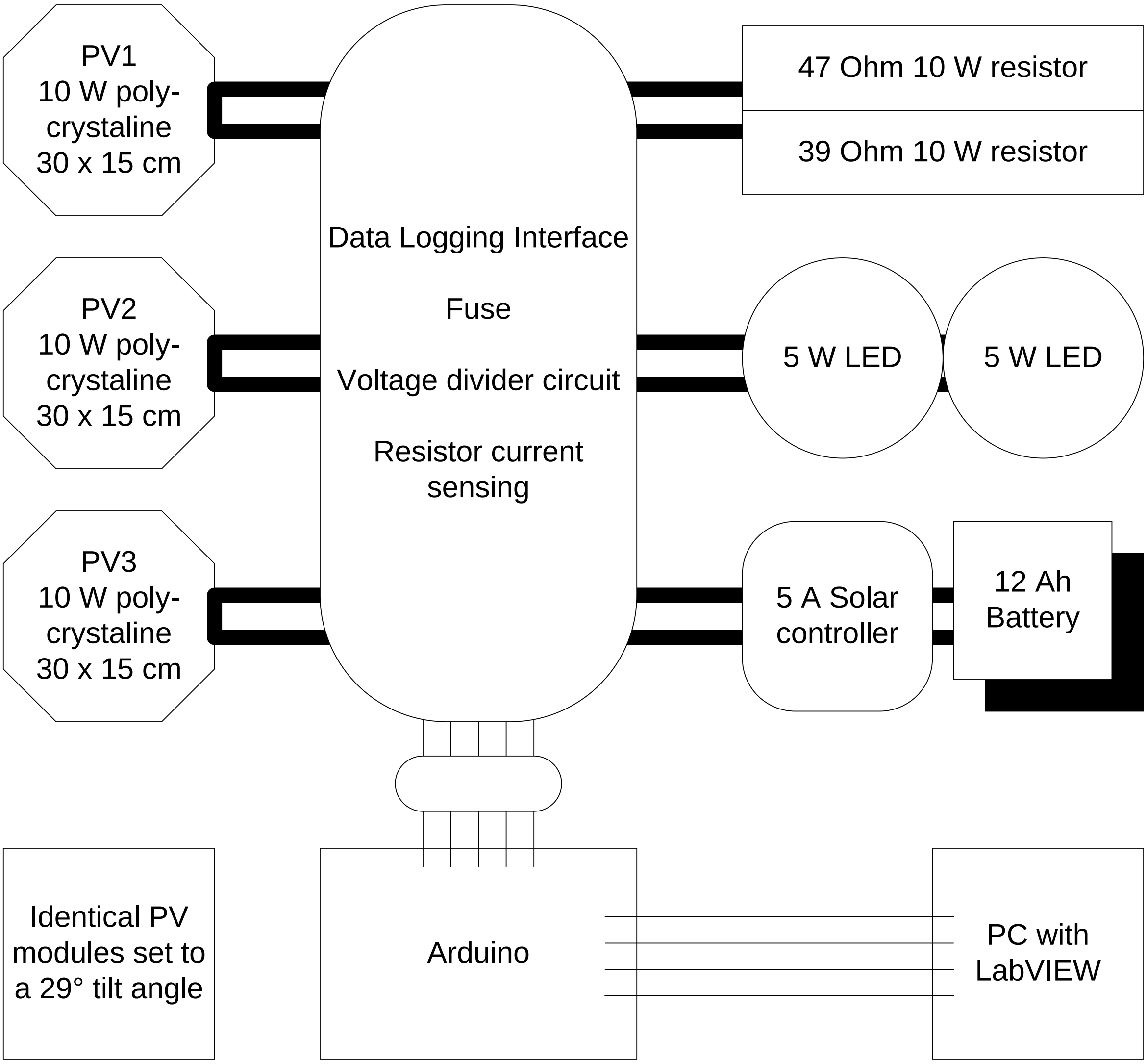


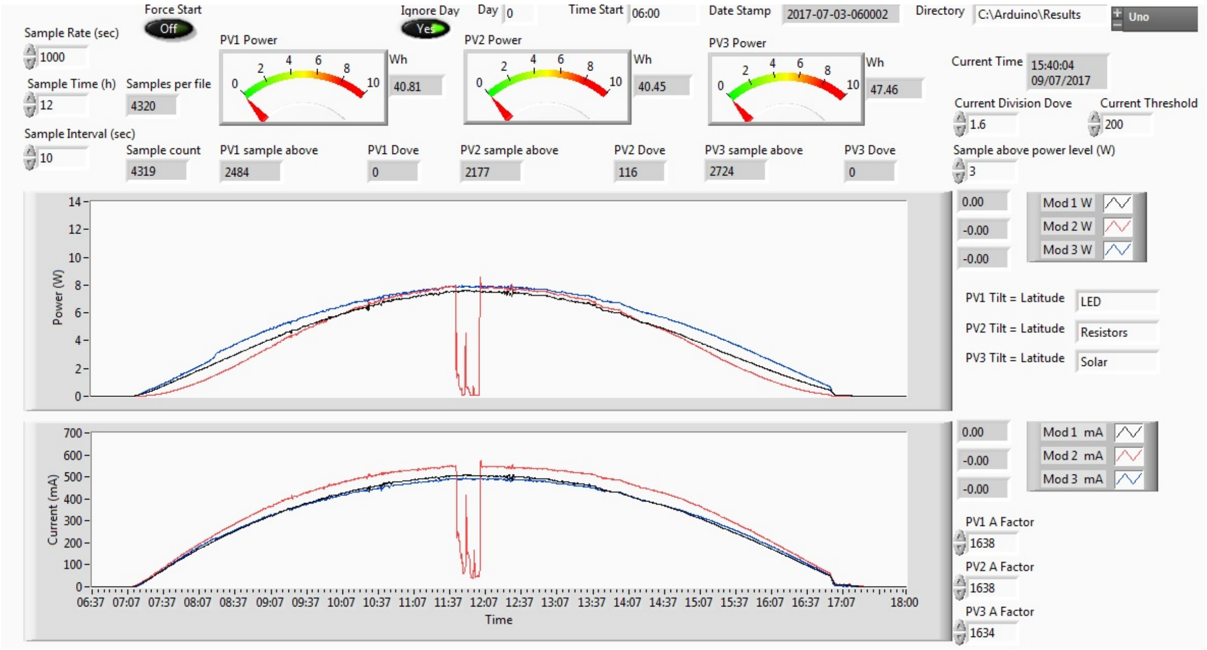
Figure 2 - Block diagram of the practical setup for the time period from 17 February 2017 to 21 August 2017

Each load was connected in series with a 6 Ohm 10 W series resistor for current sensing measurements. A simple voltage divider circuit was used to ensure that the input voltage to the Arduino UNO board would never exceed 5 V. The three PV modules were mounted onto an aluminium frame and set to the same tilt angle of 29° (also same orientation angle of 0° N), equating to the latitude value of 29° for the Central University of Technology in the Free State province of South Africa (Hertzog & Swart, 2015a, 2015b). This area is known as a semi-arid part of South Africa, where around 55% of its annual rainfall occurs between January and April (Snyman et al., 1987), with very little rainfall occurring between May and August. The output power of these PV modules was recorded and analyzed using LabVIEW software in conjunction with an Arduino UNO board. The reliability and validity of the electronic measurements where obtained by first calibrating the three PV systems (28 October 2015 – 16 February 2016). This process was discussed by Swart and Hertzog (A.J. Swart & P.E. Hertzog, 2016). The research methodology is presented next.

Research methodology

An experimental research design was used. The system was initially set up and calibrated over a three-month period (28 October 2015 – 16 February 2016). The three identical PV modules (from the same batch and same manufacturer) were set to the same tilt angle of 29°. Different unique power loads were then connected on 17 February 2017, resulting in only one different variable between the three systems. All other variables were kept constant for the three systems (environmental, orientation, tilt, etc.). However, it is important to note that the PV modules were first installed in October 2015, resulting in a total of two years of experimental (empirical) data.

Voltage readings were obtained by using a standard voltage divider circuit (147 kΩ resistor in series with a 100 kΩ resistor). The obtained values are multiplied by a predetermined factor for calibration and to compensate for any interface losses, being displayed on the front panel of the LabVIEW software that is visible to the user. This value is then filtered by a Butterworth Filter to reduce high frequency components or noise that may originate from the Arduino's analog read circuit or from the data logging interface. The user interface is shown in Figure 3.



Force Start: Off
Ignore Day: Yes
Day: 0
Time Start: 06:00
Date Stamp: 2017-07-03-060002
Directory: C:\Arduino\Results
Uno
Sample Rate (sec): 1000
Sample Time (h): 12
Samples per file: 4320
Sample Interval (sec): 10
Sample count: 4319
PV1 Power Wh: 40.81
PV2 Power Wh: 40.45
PV3 Power Wh: 47.46
Current Time: 15:40:04 09/07/2017
Current Division Dove: 1.6
Current Threshold: 200
PV1 sample above: 2484
PV1 Dove: 0
PV2 sample above: 2177
PV2 Dove: 116
PV3 sample above: 2724
PV3 Dove: 0
Sample above power level (W): 3
PV1 Tilt = Latitude: LED
PV2 Tilt = Latitude: Resistors
PV3 Tilt = Latitude: Solar
PV1 A Factor: 1638
PV2 A Factor: 1638
PV3 A Factor: 1634

Figure 3 - Screen shot of the LabVIEW interface showing the performance of the three PV modules for 3 July 2017

Current measurements are obtained by measuring the voltage across a low value high power precision resistor (6 Ohm 10 W 1%). Multiplying the voltage and current readings within LabVIEW yields power readings (in Watts) that are written to a matrix for recording purposes. The instantaneous readings per sample are also shown on the user interface, as shown in Figure 3 (data represents 3 July 2017, where the three power curves of the different load profiles seem to be very similar – far right-hand circle shows which loads were connected to which PV modules). The total amount of power extracted per day for each PV system with its own unique power load is then written to a singular text file for further analysis (Wh value next to the power scale showing the numerical values of 0 – 10). The results from this text file is then analysed for the 2-year period. It contains the date stamp, power count above 3 W (number of 10 second intervals per day in which the PV module provides more than 3 W to its associated power load), maximum Wh values per day and maximum PV surface temperature per day.

Results and discussions

The analysis of the recorded data is shown in Figures 4 through 7. Figure 4 highlights the maximum recorded surface temperature (which came from PV3) of the three PV modules for the 2-year period. This suggest that the three modules were exposed to high temperatures, as PV3 regularly reached the 50ºC mark for the summer season (November through April of 2016 and 2017). This would cause a faster degradation of the PV cells as compared to cooler atmospheric environments.

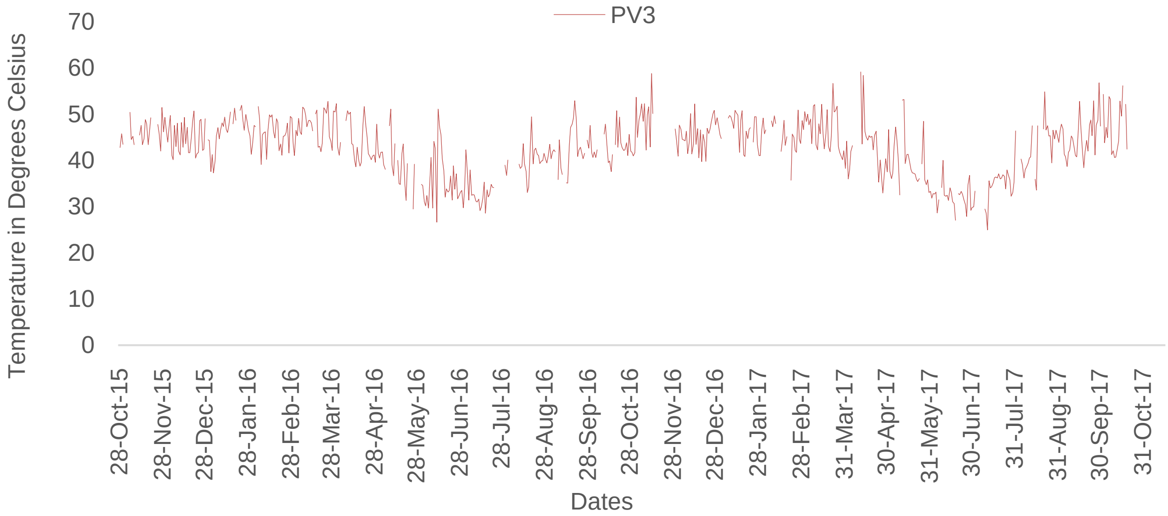


Figure 4 - PV3 surface temperatures for a two-year period

The power difference between the three PV modules is shown in Figure 5, where PV1 is contrasted to PV2 and PV3 is contrasted to PV2. The period from 28 October 2015 to 17 February 2016 was used for setup and calibration purposes, which was detailed by Swart and Hertzog (A.J. Swart & P.E. Hertzog, 2016). The major portion of Figure 5 (17 February 2016 through 8 May 2017) indicates that PV1 (connected to the load resistor) produced, on average, 6 W less than PV2 (connected to the LED lamp), while PV3 (connected to the solar controller) produced, on average, 1 W more than PV2 (connected to the LED lamp). Results remain fairly consistent for this major portion of the figure. PV3 (solar controller) does extract more energy than PV2 (LED lamp) for February through April (summer seasons for 2016 and 2017), but PV2 (LED lamp) extracts more energy than PV3 (solar controller) for May through July of 2016 (winter season). PV1 (load resistor) consistently extracts less energy than PV2, and subsequently than PV3. Its profile would typically fall in between the dotted black line and the solid red line shown in Figure 5.

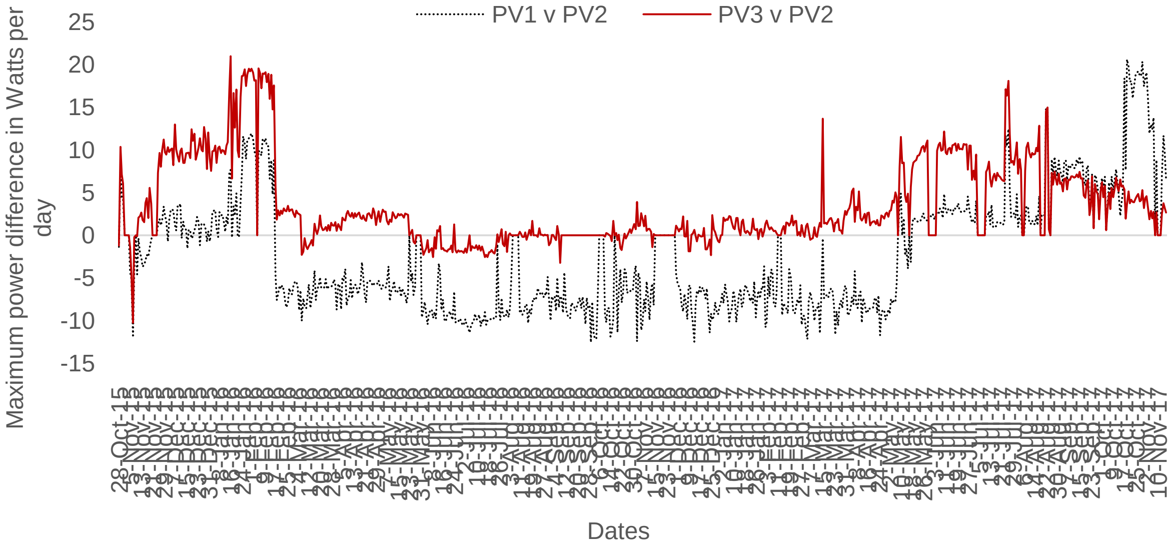


Figure 5 - Power difference (shown in Watts) between PV1 and PV2, and between PV3 and PV2, for a two-year period

This suggests that a solar controller and LED lamp respond equally well as load resistors for pico-solar systems, with variations between summer (solar 3.9% more than the LED) and winter seasons (LED 1.5% more than the solar). This confirms previously published work in this regard (Swart & Hertzog, 2017). However, this is not observed from 8 May 2017 onwards, as PV1 has now been connected to the LED lamp and PV2 to the resistor load (see Figure 3 for the load profile connections on the right-hand side). PV1 (connected to the LED lamp) now extracts more energy than compared to PV2 (connected to the load resistor) while PV3 (still connected to the solar controller) rises to around 5 W more than PV2 (load resistor). Then on 22 August 2017, all three PV modules are connected to identical LED lamps. PV1 and PV3 now follow a similar curve.

However, it is expected that PV2 should follow this same curve, as it now has the same load profile. In other words, the two curves shown in Fig. 5 (differences between PV1 and PV2 and between PV3 and PV2) should ideally be around the 0-value mark (no perceived differences should exist as they have the same load profile). This does not materialize, indicating that PV2 has significantly reduced in performance as compared to PV1 and PV3. Recall that these three modules had consistently been working since 28 October 2015, which seems to indicate that PV2 has degraded more significantly that PV1 and PV3. These modules would have been exposed to both high temperatures and many dust storms during the 2-year period. Instead of replacing PV2, it was decided to replace PV1 and compare its new performance to that of PV3, as they had followed a parallel power curve since 28 October 2015.

PV1 was replaced with a brand-new PV module that was manufactured in 2017. It had never been used before. Immediately, a major difference occurred, as seen from 17 October 2017 onwards. PV1 (a brand-new PV module manufactured early in 2017) now produced approximately 15 W more than PV3 (well-used 2-year old PV module that had reached 50°C on a regular basis). However, the graph tends to suggest that this major difference is reducing with time. Further empirical results will confirm this.

Figure 6 (a) further validates that the solar controller (connected to PV3 representing the outer circle) generally extracted more electrical energy than the LED lamp (connected to PV1) and the load resistor (connected to PV2), when considering the power level count. The LabVIEW system was designed to count the number of 10 seconds intervals in which the PV modules produced more than 3 W. The median (2228), the average (1953) and the maximum (3199) counts for PV3 are more than that of PV1 and PV2. This indicates that PV3 was the first to reach the 3 W mark early in the morning, producing 3 W for a longer period of time than compared to PV1 and PV2.

Figure 6 (b) shows the total Watts produced per day for the three PV modules. PV3 produced the highest median (53 W) and average value (48 W) for output power over the 2-year period. However, the maximum power produced for one day was achieved by PV1 (82 W) when it was replaced with a newly manufactured PV module in 2017. This confirms that both consistent use and high temperatures do degrade PV cells, as the newly installed PV module outperformed PV2 and PV3.

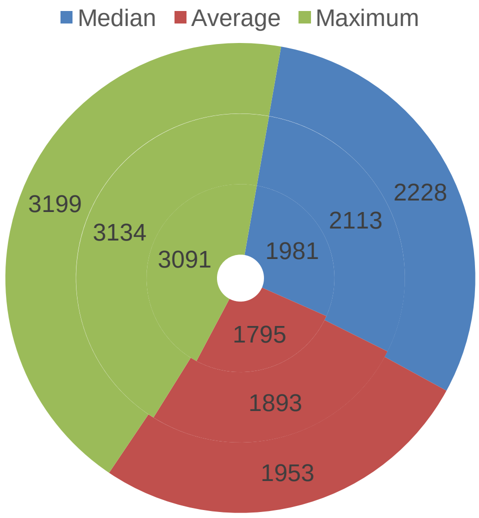


Figure 6 - Power statistics for the 2-year period based on:
***(a – Left)** power count value above 3 W (PV3 outer circle, PV2 middle circle and PV1 inner circle)*
***(b – Right)** Watts per day (PV3 outer circle, PV2 middle circle and PV1 inner circle)*

Figure 7 illustrates the frequency count values (number of days for which each PV module produces a specific amount of Watts per day). All three PV modules produced 10 W or less for approximately 50 days of the 2-year period. However, PV3 produced more than 70 W for 204 days within the 2-year period, which is more than PV2 (137 days) and PV1 (85 days). This suggests that PV3 produced more electrical energy for longer periods of time during the day while also producing higher values of electrical energy due to its connection to a solar controller.

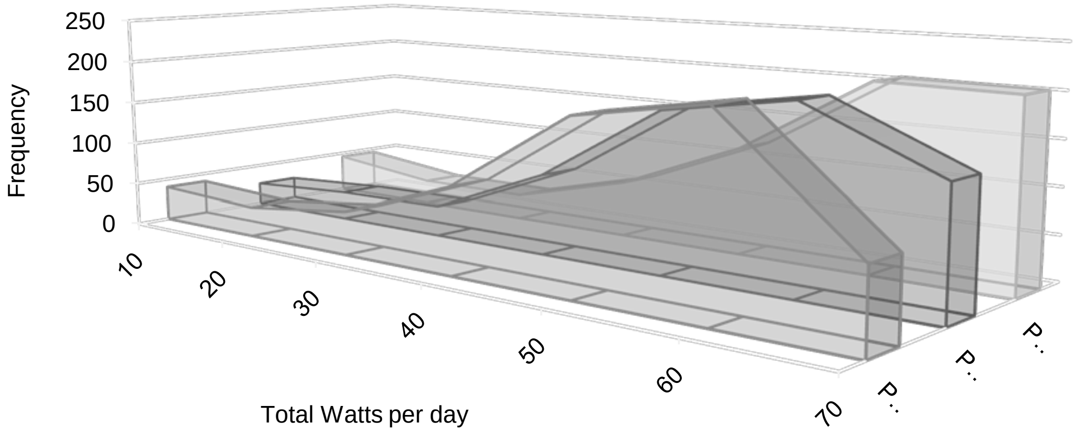


Figure 7 - Frequency of Watts per day generated by the PV modules for the 2-year period

Conclusion

Two key anomalies were identified. Firstly, the abnormal degradation in the output power of a well-used PV module. Secondly, the abnormal improvement in the output power of a newly installed PV module.

PV2 shared the same atmospheric conditions as PV1 and PV3 over the 2-year period. It was connected to a load resistor for the last 6 months, which cannot be faulted for the abnormal degradation in output power as PV1 was connected to this same load resistor for the first 18 months. However, PV1 did not exhibit the same abnormal degradation as PV2 did over the last 3 months of the period. PV2 did not follow the same curve as compared to PV1 and PV3, despite having the same load and being exposed to the same atmospheric conditions for the last 3 months of the 2-year period.

PV1 was replaced with a newly manufactured module, after which it produced approximately 15 W more than PV3 which produced the highest power value over the 2-year period. Two plausible reasons exist for this. Firstly, the new module installed for PV1 may have a higher efficiency, as it was manufactured 3 years after the original module which was used. Secondly, PV3 would have degraded by approximately 2.4% over the 2-year period, which is in-line with published research (Bartolo & Yousif, 2017).

Another key observation relates to the similar performance of LED lamps and solar controllers as viable power loads for testing PV modules in pico-solar systems. The LED lamp outperformed the solar controller in the winter season (1.5% more output power) while the solar controller outperformed the LED lamp in the summer season (3.9% more output power). The resistor proved to be a poor power load.

Time has revealed a better understanding of these PV modules in that one PV module degraded faster than other identical PV modules over a 2-year period in a semi-arid region of South Africa. A key recommendation is to initiate an annual maintenance program that may check the output power and performance of individual identical PV modules within a greater array. The contribution of this empirical data for a pico-solar system over a 2-year period may further be used to design and improve simulation software models that are often used as the starting point for determining the viability of a given PV installation within a specific atmospheric environment.

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