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Evaluating the Performance of Small-Scale PV Modules in a Semi-Arid Area to Identify any Anomalies

Arthur James Swart* and Pierre Eduard Hertzog

Faculty of Engineering Built Environment and Information Technology, Central University of Technology, Bloemfontein 9301, South Africa; drjamesswart@gmail.com

Abstract

Objectives/Methods: Performance analysis of PV systems can leads to system optimization and sustainability. The purpose of this study is to evaluate the performance of three identical PV systems in a semi-arid region in order to identify and rectify any anomalies that can affect the overall efficiency of a renewable energy system. An experimental research design is used where the practical setup consisted of three identical PV systems (10 W PV modules connected through a data logging interface circuit to LED lamps that serve as the load resistances). Initial Watt hour per day results indicated four periods of anomalies, where the fourth period could not be explained. **Findings/Application:** An infrared thermal image taken during this period revealed a different location of a hotspot for a module termed PV3 that also had a higher surface temperature when compared with the other two modules. Instantaneous power measurements for that fourth period from this possible error-prone PV module further revealed an approximate 9% reduction in output power as compared to the other two modules. It is recommended to make use of thermography and instantaneous output power measurements of PV modules or arrays in order to try and identify and replace any possible faulty modules.

Keywords: Arduino, Efficiency, LabView, Performance, Southern Hemisphere

1. Introduction

Fault-finding is a process of elimination using logical reasoning, where one attempts to eliminate logically and systematically what is right in a circuit in order to be left with what is wrong. It is not a process of speculation, but rather grounded on evidence and measurements. It forms an integral part of the maintenance and repair of any technologies. Fault-finding has been described as a type of human problem-solving behaviour, with the attempt to identify errors in a system and repair or replace any faulty components in order to restore the system to normal functioning[1]. Fault-finding is a major undertaking in the assembling and maintenance of large scale Photovoltaic (PV) solar farms, due to the time requested for manual searching[2].

Time domain reflectometry has been used to simplify this process by analysing the waveforms obtained when a step-voltage excitation is propagated down the electrical line connecting the PV generators to the inverter. One is able to detect, identify and localise the most common fault conditions, such as circuit breaks, insulation defects and wiring anomalies. Another technique used to simplify the process involves the use of fault detection algorithms[3]. It is based on the comparison of simulated and measured yields by analysing the losses present in the system. Identifying the kind of fault is carried out by analysing and comparing the amount of error deviations

**Author for correspondence*

of both DC current and voltage with respect to a set of error thresholds (or a reference value) evaluated on the basis of a fault-free system.

In utility scale PV farms, this type of monitoring focuses on series currents of multiple modules, with the performance of individual PV modules not been tracked, which is a key element in an array[4]. One error-prone PV module, or cell, can negatively affect the performance of an entire string[5]. It is, however, challenging to identify faults (they may include hot spots or other types of failures) at this individual PV module level. To overcome this challenge, some tests have been proposed that include IV curve tracing, electroluminescence and thermographic tests. Aerial thermographic inspections, in which a drone carries athermographic sensor, are becoming popular for the detection of hot spots as it reduces the inspection cost and is less time consuming than manual thermographic inspection[4].

However, what percentage of output power is lost when considering error-prone PV modules. One study in 2012 suggested that roughly 6% of expected output power is lost as a result of undetected faults in PV modules[6]. However, would this hold true in a semi-arid region, where dramatic ambient temperature fluctuations can occur between winter (less the 0°C) and summer (about 40°C)? Would the on-going effects of climate change also not accelerate module degradation? Error-prone PV modules need to be identified early and replaced in order to ensure that the overall efficiency of the renewable energy system remains high. This is due to the fact that a key requirement for PV modules, or arrays, is that all PV cells, or modules, need to be roughly identical[7]. Mismatch power losses arise when cells or modules with different current–voltage characteristics are interconnected[8]. Shading, construction tolerances and different orientations of PV modules in an array could generate this mismatch[9,10], leading to an overall drop in the output power and efficiency of the renewable energy system[11].

The purpose of this study is therefore to evaluate the performance of three identical PV systems in a semi-arid region in order to identify and rectify any anomalies that can affect the overall efficiency of a renewable energy system. The paper firstly considers PV module construction and degradation, after which the research site and practical experimental setup is described. The research methodology and results (mainly tables and sketches) are given next, followed by the conclusions.

2. A Synopsis of PV Module Construction and Degradation

The majority of PV cells (polycrystalline and monocrystalline) are manufactured from wafers of crystallized Silicon or from thin film amorphous Silicon[12]. The basic manufacturing process involves processing Silicon as a raw material into large ingots. Three general accepted techniques exist for this process that includes the Czochralski process, the directional solidification technique and various casting techniques[13]. Different manufacturing methods are used to achieve different efficiencies that impact on the cost and size of the PV cell. Differences between cells do arise from the unavoidable fabrication spread of the Silicon[14] that arises in the manufacturing process. Notable differences also exist in the electrical characteristics of nominally identical PV cells.

Added to these manufacturing challenges is the effect of degradation. The main modes of module degradation identified in the literature are corrosion, discoloration, delamination, and breakage[15]. These factors involve environmental parameters such as temperature, humidity and UV radiation. Delamination is more proactive in degradation which refers to electrochemical corrosion. Delamination of the transparent conductive oxide layer from the front glass surface affects module glass substrates which corrode as a result of moisture ingress and reverse bias[16]. It has further been shown that PV cells degrade faster in hotter climates due to long-term thermal ageing[17] where they may lose their structural integrity[18]. PV module degradation is usually gradual, being caused by two main factors: an increase in the series resistance or decrease in the shunt resistance of the module[19]. Changes to these resistances are detrimental to PV module performance, as it results in loss of output power.

From the above discussion, it is evident that a key parameter that changes within operational PV modules is the internal resistances of the individual cells. As this internal resistance changes due to various factors, less current tends to flow, reducing the overall output power of the cell. This effect can be magnified if multiple cells, or modules, are connected in series as the entire string is affected by a singular error-prone cell or module. This generally leads to the formation of hot spots where a large number of series connected cells are affected by a singular error-prone cell. This may force the entire string to operate at a lower output power than desired[20]. These hot spots are problematic as they further accelerate cell degradation and lower system performance[21]. These results in a vicious circle where one factor may lead to another factor causing more degradation that may be termed "stimulated degradation". This is similar to stimulated emission in a laser device, where one emitted photon can stimulate another atom or molecule to release more photons. Identifying these hotspots and correlating them to lower output power performances requires the use of a practical setup.

3. Research Site and Practical Setup

The research site is located in the middle of South Africa that is well-known as a semi-arid region (Figure 1). This region has a normal daily solar radiation of between 4.5 and 7 kWh/m^2/day, making it ideal for solar renewable energy research. It has an average yearly precipitation of around 550 mm, where more than half of its annual rainfall occurs between January and April[22,23]. The winter season is very dry with numerous dust storms occurring in August and September.

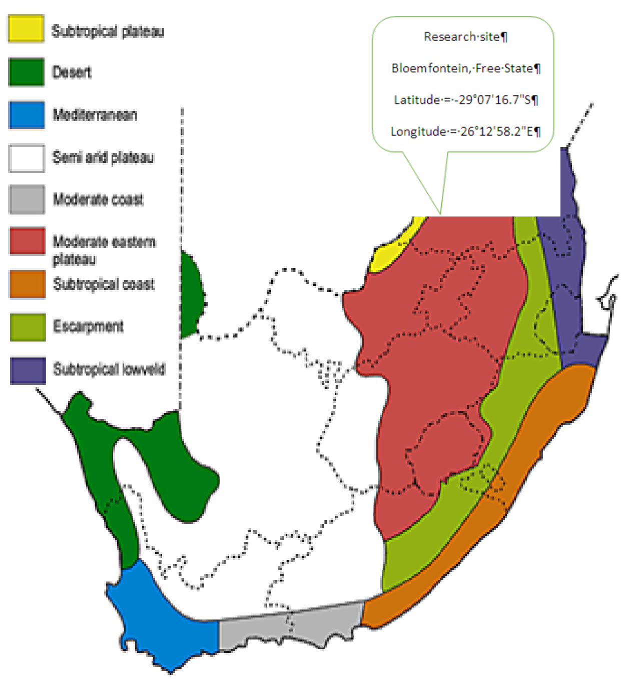

Figure 1. Climate features of South Africa with the research site coordinates.

The exact coordinates of the research site are shown in Figure 1, where the latitude value is used for the tilt angle, while the orientation angle is set to 0°N. The practical setup includes three identical PV systems, each with a 10 W polycrystalline PV module (Isc = 0,78 A and Voc = 20,8 V with NO bypass diodes installed), two regulated LED lamps (5 W each), a data interface circuit, an Arduino Mega board and LabView. This is typically called a pico-solar system, as the output power is less than 10 W[24]. The PV modules are fixed to an aluminium frame that has been installed on a second-floor balcony facing due north (Figure 2).

Figure 2. Aluminum frame used to mount three identical PV modules; tilt angle = latitude.

Maximum Power Point Tracking (MPPT) systems are usually employed to enable a PV module, or array, to operate at its most efficient point. However, when testing pico-scale solar system, regulated LED lamps have been found to perform similarly to such MPPT systems[25–27]. This eliminates a number of unknown variables related to storage devices that are usually required with MPPT systems or with solar chargers. In this practical setup, 2 × 5 W regulated LED lamps were directly connected to the 10 W PV modules via a data logging interface circuit comprising a voltage divider circuit and a shunt resistor.

Voltage sensing of the output of the PV modules is accomplished using a voltage divider circuit (147 kΩ and a 100 kΩ in series). Current sensing is accomplished using a shunt resistor (2 × 12 Ohm 5 W resistors). All resistors have a tolerance value of 1%. These sensing circuits provide signal conditioning that limits the input voltage to the Arduino Mega board (input limit of 5 V). The shunt resistor is preferred to that of a hall-effect current sensor that usually has a poor linearity for current values below 1 A. Higher current values demand the use of hall-effect current sensors[28] in order to limit heat energy that shunt resistors produce for currents above 1 A. The voltage across this shunt resistor is measured and then converted to a current value in LabView.

All voltage measurements are made using the analogue input ports on an Arduino Mega board (16 analogue input channels are available). Calibration factors are incorporated into LabView that can be modified in real time during a sampling period. The calibration process was reported on by[29]. The research methodology is presented next.

3. Methodology

An experimental research design is used with quantitative data. It can be equated to a longitudinal study, as the same PV modules are exposed to varying environmental conditions over an extended period of time. A longitudinal study involves observing the same variables repeatedly over a period of time and is commonly encountered in psychology, social sciences, economics and medical sciences. The varying environmental conditions exist due to the uniqueness of the research site, that experiences major temperature fluctuations between winters (less the 0°C) and summer (about 40°C). Dust storms are the norm in early spring (August and September) whiles the majority of rain falls in early autumn (March and April). Quantitative data is gathered for the time period between 01 January 2018 and 01 February 2019.

Three identical PV systems were originally installed in 2015 as part of another research project. On 31 January 2018, (after being exposed to the same environmental conditions for about 4 years), the three identical systems were again calibrated to ensure accuracy of any new measurements. Voltage and current measurements were then recorded every day between 6 am and 6 pm using an Arduino Mega board in conjunction with LabView. Watt hours (Wh) were calculated in LabView using these measurements. The sampling interval was set to 10 seconds, which means that a total of 4320 samples were obtained for each day. At the end of the sampling period, the total Wh obtained for a day is written to a singular text file in order to simplify the analysis.

Screenshots of the front panel of LabView are also acquired to visually indicate any differences between the three identical PV systems. The main anomaly relates to any difference in output power of the three PV modules that can be discerned by a severe dip in the power curve for a given day. A FLIR 302 camera was employed to capture the infrared thermal image of the back panel of the PV modules. This is done in order to ascertain any thermal image differences, or hotspots, between the PV modules, and then correlate it to the Wh results available for a given day.

4. Results and Discussions

Figure 3 shows the total Wh per day for the time period that was obtained from MS EXCEL using the data from the singular text file. Four periods of anomalies have been marked. Period 1 relates to the calibration process

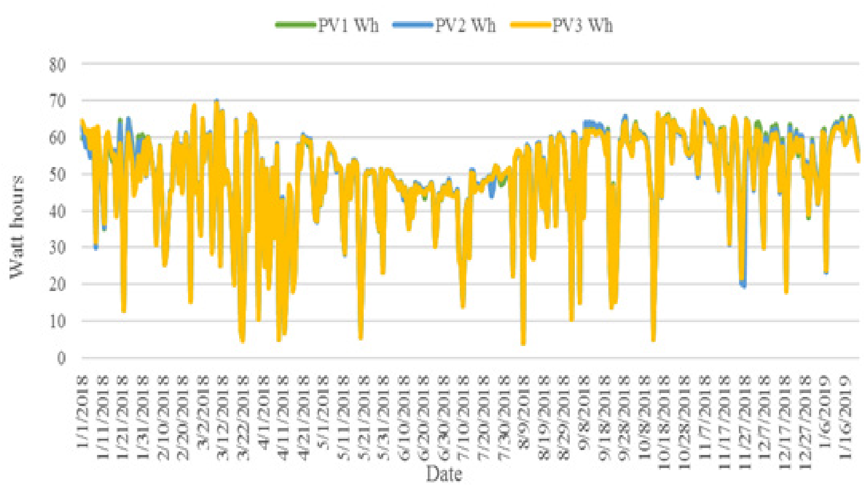

Figure 3. Output power performance of three identical PV modules over 13 months.

that can be ignored in the overall analysis. Period 2 and Period 3 relate to significant pigeon droppings that had to be removed from the PV modules. Hertzog and Swart have published results on detecting the presence of pigeons on 10 W PV modules, often leaving droppings behind that interrupt the direct beam radiation of a specific cell[30]. Period 4 is the one of main concern. No pigeon droppings where found on the PV modules and no other interruptions in the direct beam radiation where identified. This led to the conclusion that one of the PV modules must have been more severely affected by the environmental conditions and now be producing less power than before. PV3 was identified as an error-prone module based on the following discussion.

The three PV modules were set to the same tilt and orientation angle on 31 January 2018. Recall that each PV module is connected directly to 2 × 5 W LED lamps that serve as the load resistance. No MPPT, solar chargers or storage devices were used. The effectiveness of these lamps in providing a good point of operation for the PV modules has been substantiated by[26, 27]. All three PV modules now produced the same output power curve. An example of this is shown in Figure 4 that presents a screenshot of the front panel of LabView that was developed as part of the data acquisition system.

The top of the screenshot shows three Wh values representing the total Wh produced for 15 May 2018 (Date stamp start visible on the top right). There is only a 46 mW difference in the Wh produced between PV1 and PV2, while a 7 mW difference is observed between PV1 and PV3. This equates to a maximum difference between the three PV modules of less than 0.25% (Table 1). The power curves of the three PV modules are identical for this specific day where much cloud movement occurred after 11:04 am. The initial difference between the three PV modules at 08:04 am may be attributed to shading caused by a tree in front of the second-floor balcony that interrupts direct beam radiation during the winter periods. Note also the close similarity between the Power sample values for each PV module that indicates how often the module produced more than 3 W for the day (Table 1 indicates a difference of less than 0.31%). Each sample

Table 1. Comparison between the three identical PV modules for 15 May 2018

Parameter \ PV module number	PV1	PV2	PV3
Watt hours produced for the day (Wh)	18.202	18.248	18.209
Difference in percentage between the Wh	1 and 2 = 0.25%	2 and 3 = 0.21%	1 and 3 = 0.04%
Instantaneous output power (mW)	330	340	330
Power sample count above 3 W	2252	2259	2255
Difference in % between the sample counts	1 and 2 = 0.31%	2 and 3 = 0.17%	3 and 1 = 0.13%
Amount of time above 3 W (h:min:sec)	6:15:21	6:16:30	6:15:50

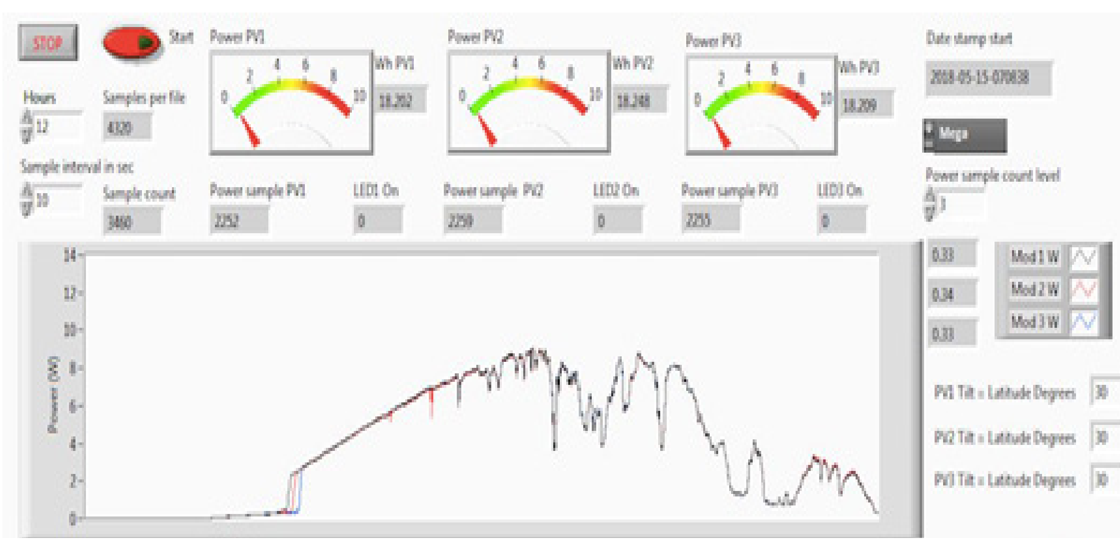

Figure 4. Screenshot of the front panel of LabView showing identical power curves

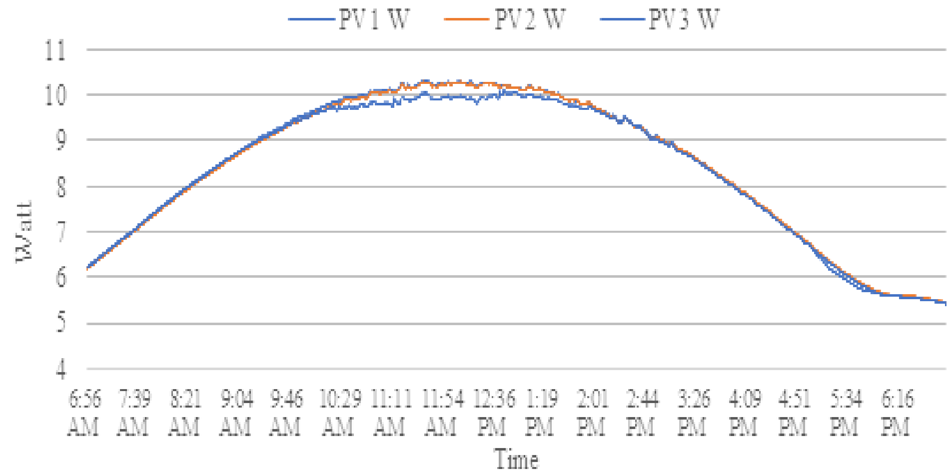

Figure 5. Output power results showing a power curve anomaly for PV3 on 24 Jan 2019.

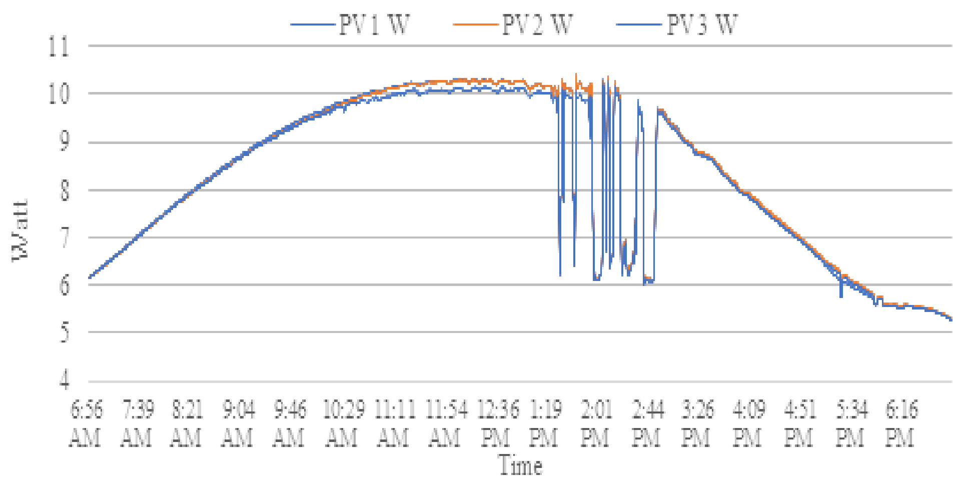

Figure 6. Output power results showing a power curve anomaly for PV3 on 7 Feb 2019.

equates to 10 seconds (Sample interval in sec visible on the top left) that results in an average time of 6 hours and 16 minutes that the PV modules produced more than 3 W.

The output power curves of the three PV modules were then analysed for 24 January 2019 (Figure 5) and for 7 February 2019 (Figure 6). These dates fell within the fourth period identified in Figure 3. A clear difference between the output power curve of PV1 and PV3 is discerned.

An infrared thermal image was taken around 12:00 pm on these two days in order to try and ascertain any differences between them that could be linked to the power curve anomaly. The exact differences are tabulated in Table 2 that shows PV3 to have a higher back surface temperature than PV1 (2.1°C higher). The location (top of the module) of its hotspot temperature (Figure 7) was also different from that of PV1 and PV2 that had similar hotspot locations and temperatures (difference of only 0.8°C). Another set of images were recorded for 7 February 2019, and are shown in Figure 8. The location of the hotspot for PV1 and PV2 is still consistent, although different from that in Figure 7. However, the location of the hotspot for PV3 (seems to be the error-prone module) remains at the top of the module, similar to that shown in Figure 7 (right-hand image). Its surface temperature continues to be higher than that of PV1 and PV3 (4.9 °C higher).

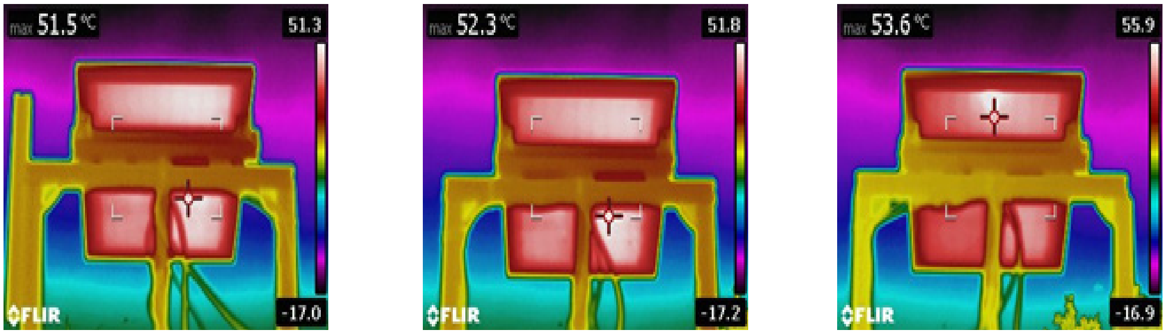

Figure 7. Infrared thermal images (PV3 is on the right-hand side) taken on 24 January 2019.

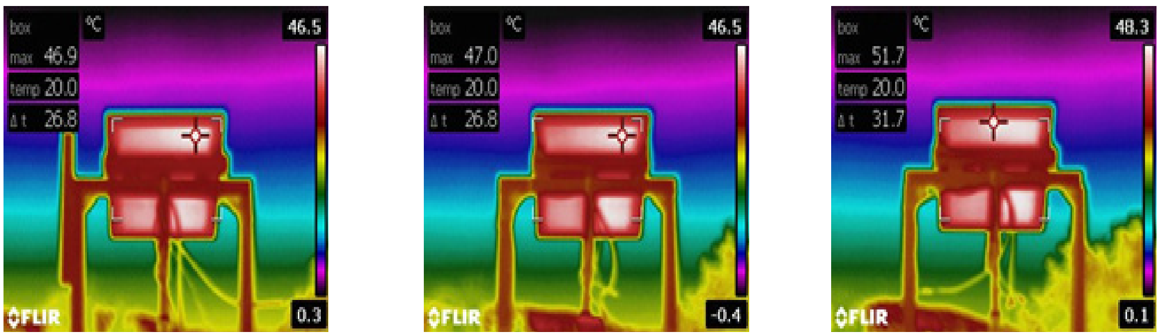

Figure 8. Infrared thermal images (PV3 is on the right-hand side) taken on 7 February 2019.

Table 2. Comparison between the identical 10 W PV modules for 24 January 2019.

PV module number / **Parameter**	**PV1**	**PV2**	**PV3**
Temperature - Figure 7	51.5°C	52.3°C	53.6°C
Difference in temperature - Figure 7	1 and 2 = 0.8°C	2 and 3 = 1.3°C	1 and 3 = 2.1°C
Position of the hotspot - Figure 7	Bottom right	Bottom right	Top middle
Total Wh for the day	52.2 Wh	52 Wh	51.5 Wh
Instantaneous output power at 12 pm	9.48 W	9.41 W	8.57 W
Instantaneous output power difference	1 and 2 = 70 mW	2 and 3 = 840 mW	3 and 1 = 910 mW
Difference in terms of percentage	1 and 2 = 0.7%	2 and 3 = 8.9%	3 and 1 = 9.6%

Table 2 also presents the instantaneous output power for PV1 and PV2 (very similar with only a 70 mW difference), while PV3 is significantly lower with a value of 8.57 W (difference of 840 mW and 910 mW). The total Wh produced by PV3 is also lower than PV1 and PV2, although only by 700 mW. These values were obtained from a text file which LabView writes to the hard drive after recording 4320 samples for each day (10 second intervals from 6 am to 6 pm).

Figure 9 shows the maximum and minimum recorded temperatures of the back surface of the three PV modules, obtained using an Arduino temperature sensor (DS18B20). The four periods labelled in Figure 3 cannot be identified in this result. A close similarity exists between the minimum temperatures (R = 0.998) and the maximum temperatures (R = 0.992) of the PV modules. However, the maximum temperatures do reveal the extent of the temperature fluctuations for the research site between summer (maximum back surface temperature of the PV module equals 60°C) and winter (back surface temperature equals 34°C on 14 July 2018).

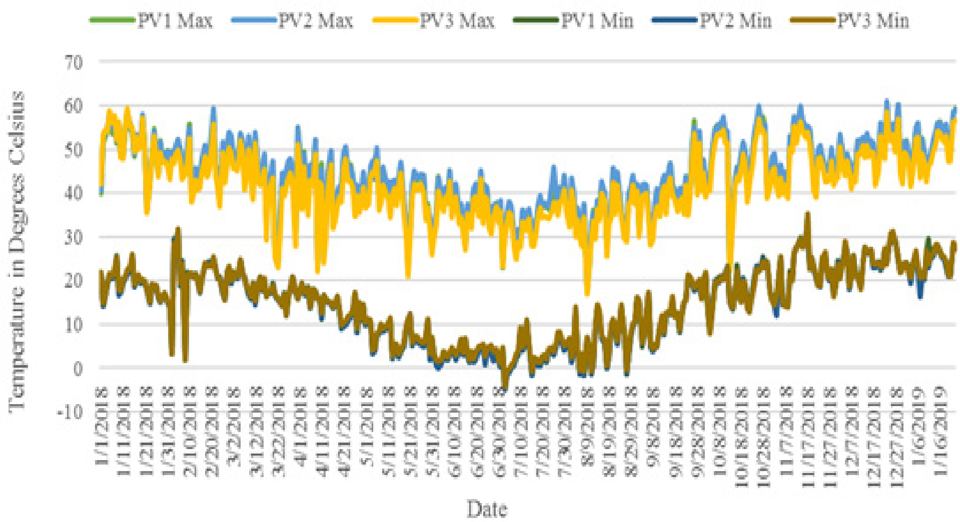

Figure 9. Maximum and minimum temperature of the back surface of the three PV modules.

6. Conclusions

The purpose of this study was to evaluate the performance of three identical PV systems in a semi-arid region in order to identify and rectify any anomalies that can affect the overall efficiency of a renewable energy system. The Wh results indicated four periods of anomalies. Periods 1 through 3 could be attributed to either calibration or shading caused by pigeons. Period 4 could not be explained. It was therefore assumed that PV3 had been affected to a greater degree by the environmental conditions (including elevated temperatures) of the research site, as compared to PV1 and PV2. Recall that all these modules had operated continuously for 4 years in this environment as part of another study. The anomaly of period 4 relating to PV3 was confirmed by an infrared thermal image, that revealed a different location of its hotspot that was higher in temperature (2.1°C and 4.9°C higher) than the other identical modules. Temperature results obtained from the back surface of the PV modules, using an Arduino temperature sensor, could not verify this anomaly. The output power curve of these modules confirmed that PV3 was producing approximately 9% less in output power than compared to PV1 and PV2. It is recommended to make use of thermography and instantaneous output power measurements of PV modules or arrays in order to try and identify and replace any possible faulty modules. This may lead to the preservation of the overall efficiency of a PV system, as unwanted power reduction is mitigated.

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