Verifying an economic viable load for experimental purposes relating to small scale PV modules

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Abstract—**Optimizing the output power of any PV module requires a number of factors to be considered, including the tilt angle, orientation angle, environmental conditions and the energy management system. This system often includes a maximum power point tracker that is required to adjust a module's output voltage to a value which enables the maximum energy to be transferred to a given load. A solar controller may also be used in the energy management system to prevent batteries from overcharging, to prevent back flow of current from the batteries to the solar modules and to provide maximum reliability and service life of the whole system. However, when various parameters of PV modules need to be investigated in real life applications, what type of economic viable load is suitable for experimental purposes relating to small scale PV modules? The purpose of this paper is to present empirical evidence contrasting the performance of three identical 10 W polycrystalline modules connected to three unique separate loads. A LabView software program was developed to record and display the voltage and current measurements from the PV modules using a data logging interface circuit and an Arduino board. Results indicate that a solar controller extracts more power from a PV module (on average 3.9% more power), as compared to a regulated LED and a fixed load resistor. However, the regulated LED follows a profile similar to that of the solar controller, drawing on average 2 W less per day than the solar controller. On the other hand, the fixed load resistor draws on average 8 W less per day than the solar controller, following a profile different to that of the solar controller and regulated LED. The regulated LED is therefore verified as an economic viable load for experimental purposes involving small scale PV modules.**

Keywords— **Arduino, LabView, Metrology, regulated LED, fixed resistor, solar controller, load**

I. INTRODUCTION

"You cannot have a society where you spend more than you earn. I mean, it's just fundamentally not viable in the long run." These words, uttered by Azim Premji, an Indian businessman, pinpoint a fundamental universal principle in that one cannot use more than what one produces. This is not viable or sustainable, and will lead to ruin. This principle applies equally well to photovoltaic (PV) modules used in renewable energy systems. It is impossible to use more energy than what a PV module can provide. However, it is imperative to try to optimize the output power of a PV module. Optimum PV module installations (tilt and orientation angles) are therefore advocated [1, 2] along with maximum power point trackers (MPPT) that adjust a module's output voltage to a value which enables the maximum energy to be transferred to a given load [3]. However, many MPPT are expensive leading some to choose a more economically viable option being a solar controller that regulates current and prevents overcharging

of the storage device [4]. Both these options have been reported on in the literature as critical components on renewable energy management system.

However, are these components really necessary for determining various parameters of a PV module in real life applications? That would depend to a large degree on what applications are considered. If the maximum output power of a PV module is required under varying atmospheric conditions, then a MPPT would be required. However, if the relationship between the incident angle of light on a PV module's surface and its associated output power is to be ascertained, then a solar controller would be suitable. An even more economical viable option would be a regulated light-emitting diode (LED) that would not require a solar controller or its associated storage device.

The purpose of this paper is to present empirical evidence contrasting the performance of three identical 10 W polycrystalline modules connected to three unique separate loads in order to establish an economic viable load when considering similar output power results. These loads include a 12 V battery connected to a 5 A solar controller, 2 x 4 W 12 V non-regulated LED lamps, 2 x 5 W 12 V regulated LED lamps and 2 x 39 Ohm 10 W fixed load resistors connected in parallel. A theoretical comparison between different PV module energy management systems is firstly presented. Secondly, the research methodology is given, followed by a detailed explanation of the experimental setup. Results and conclusions complete the paper.

II. PV MODULE ENERGY MANAGEMENT

PV modules receive direct (beam), diffused and reflected radiation during varying atmospheric conditions [5]. Direct beam radiation is the component which enjoys direct line-of-sight between the sun and the PV module. Diffused radiation is the component scattered by atmospheric constituents such as molecules and clouds [6]. Reflected radiation occurs when light energy is reflected off trees or buildings towards the PV module.

There are various methods to extract the radiation received by a PV module or array. The simplest method would be to couple a PV module directly to a given load. However, this may not be the most efficient way to extract the maximum amount of energy from a PV module for any given radiation condition. An alternative, and more acceptable method, would involve the use of an energy management system that would regulate the flow of current between a PV module and a given load. This would involve the use of a MPPT or a solar controller.

The main role of a solar controller is to protect the storage device [7]. Solar controllers (also called solar regulators) are

rated by the maximum amount of current they can regulate from a PV array or module [8]. Many often include a simple switching technique (on/off) for both simplicity of design and operational reliability. Basic solar controllers are relatively inexpensive in South Africa, with a 15 A pulse width modulated version costing approximately R180 from Mantech Electronics in Johannesburg (see Table 1).

TABLE 1: Comparison of load conditions

Load condition	Principle used	Local cost	Main advantage	Main disadvantage
MPPT 10 A	Multi point power tracking	R1360	Increase in charge efficiency up to 30%	High relative cost
Solar controller 15 A	Pulse Width Modula-tion	R180	Low power applications have better energy harvesting	Less efficient than a MPPT
Regulated LED 12 V 4 W	Regulated electronic circuit	R42	Relative low cost	Difficult to predict the characteristics of the electronic circuit
Fixed resistor 10 Ohm 10 W	Resistive load	R10	Very low cost	Not efficient under varying input energy conditions

More advanced solar controllers are referred to as MPPT. Not only do they regulate the flow of current, but they also are used to extract the maximum power from one or more PV modules under various environmental and operating conditions [9]. However, they are more expensive than solar controller or regulated LED lamps.

Regulated LED lamps have the advantage of not requiring a storage device and of being relatively inexpensive. This makes them ideally suited to evaluate the applications of identical PV systems in real life scenarios, as the number of variables is reduced. It is well known that battery-to-battery variations in e.m.f at a given state of charge may be in the order of 50 mV for every 2.25 V cell, due to variations in the manufacturing process, ageing and charge-discharge cycling [10]. This may result in a variation between two identical PV systems' storage device of 13 % (0.05 / 2.25 x 6 cells per battery x 100%). This may impact negatively on a comparison study in which two or more identical PV systems are evaluated under specific conditions. Tight regulated LED current, high efficiency and satisfactory power factor have all been achieved with only one power stage within the LED [11].

Fixed load resistors are the cheapest option when it comes to load conditions for PV modules. However, its main drawback is that it severely reduces the source voltage if it is attempting to draw more current than what is available (resistor value is too small). On the other hand, it will limit the current drawn from the PV module and not use all the available current when the resistor value is too high.

III. RESEARCH METHODOLOGY

An experimental research design was used where three PV modules were set to the same tilt angle of 29º (Latitude

value of the installation site), each with its own 18 Ohm 10 W fixed load resistor. Four weeks of data (October 2015) were then recorded to observe any significant differences between the three systems, which could then be calibrated use specific factors in the software. A coefficient of variation of 1.4% was calculated indicating that all three systems were performing equally well.

The three PV modules were then connected to different load conditions, resulting in only one different variable. All other variables (environmental conditions, orientation and tilt angles, etc.) were standard for the three systems. Data was recorded from mid November 2015 through the middle of May 2016. On the 17th of February 2016, the 4 W non-regulated LED was replaced with a 5 W regulated LED. This was done to compare the results of the two unique LED configurations, while at the same time increasing the current drawn from the second PV module. The 4 W non-regulated LED lamp is a standard design with no built-in regulation circuit. However, the 5 W regulated LED lamp features new technology with a built-in regulator circuit to accommodate larger voltage fluctuations.

IV. EXPERIMENTAL SETUP

The experimental setup consists of three identical PV systems comprising 10 W polycrystalline PV modules, a data logging interface circuit, an Arduino board and LabVIEW software (see Fig. I for the block diagram). Three different load conditions are used, which include a solar controller (5 A) connected to a 12 Ah battery, two parallel LED lamps (4 W non-regulated and then 5 W regulated) and two parallel 39 Ohm 10 W fixed load resistors. Therefore, the only variable which is different between the three identical systems is the load condition.
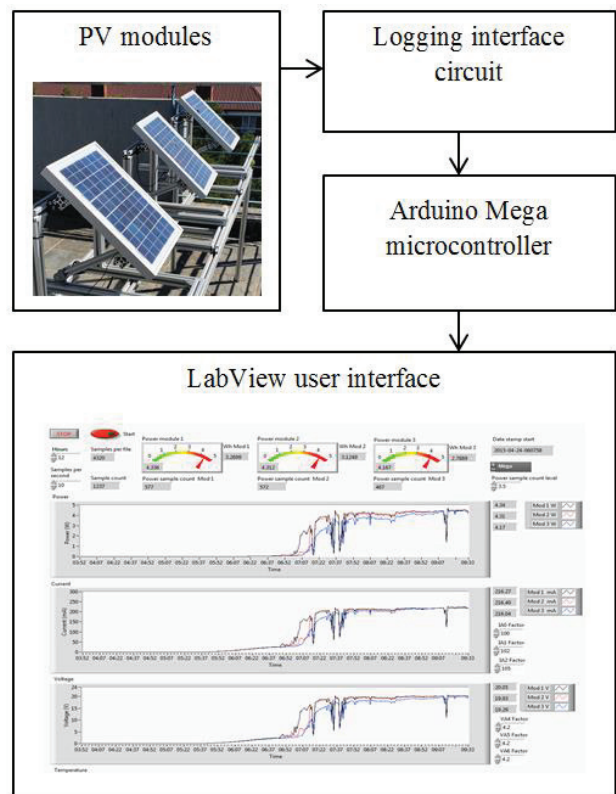

Figure I: Experimental setup

The solar controller is an entry level controller that can regulate no more than 5 A. This is suitable for use with the

10 W PV module that has a short circuit current of 0.78 A and an open circuit voltage of 20.8 V. The maximum power point voltage of the PV module is 16.5 V, with a maximum power point current of 0.61 A. Two 4 W LED's are connected in parallel to the output of the solar controller and serve as the load resistance for the battery. The solar controller regulates the current flow to these LED's, switching then either on or off depending on the state of charge of the 12 Ah battery. This ensures that optimum energy is constantly drawn from the PV module during daylight hours to charge the 12 Ah battery. A 6 Ohm 10 W series resistor is used between the solar controller and PV module for current sensing measurements.

The 4 W and 5 W LED lamps were also selected using the maximum power point voltage and current of the PV module. Two parallel 4 W 12 V non-regulated LED lamps were initially connected directly to the PV module, each in series with its own 10 Ohm 10 W resistor. This series resistor accommodates the voltage drop resulting from the difference between the PV modules output voltage and that required by the LED. A 6 Ohm 10 W series resistor is used between the two parallel LED's and the PV module for current sensing measurements. This means that the maximum series resistance for one LED branch would be 16 Ohm, resulting in a maximum current flow of 0.281 A (16.5 V – 12 V divided by 16 Ohm). However, this is for one LED branch. Two branches exist which means that 92% of the maximum power point current (0.562 A divide by 0.61 A) should be drawn by the two parallel 4 W LED lamps during the maximum period of daily solar radiation. This was eventually changed to a 5 W 11 – 13 V regulated LED lamp to enable a higher amount of current to be drawn from the PV module. Using LED lamps, instead of a MPPT or a solar controller with a given load, has been used before as an economical viable load in determining the acceptance zone and switch-on times of specific PV modules [12, 13].

The two parallel 39 Ohm 10 W resistors were also selected using the maximum power point voltage and current of the PV module. The parallel branch results in a series resistance of 19.5 Ohm which is directly connected to the PV module by means of a 6 Ohm 10 W series resistor that is used for current sensing measurements. This means that the total load resistance for the PV module is 25.5 Ohm, resulting in a maximum current flow of 647 mA during the maximum period of daily solar radiation. Using a fixed load resistance, instead of a MPPT or a solar controller with a given load, is an effective and easy method to start loading PV modules located outdoors for measurement purposes [14, 15]. Table 2 summarizes the load conditions.

The data logging interface circuit has been reported on by a number of researchers [16, 17] and provides power conditioning between the PV system and the Arduino board which is connected to the personal computer and interfaced with LabVIEW software. The use of the Arduino board and the LabVIEW software as a data logger has been reported on by Hertzog and Swart [1, 18].

The three PV modules were mounted onto an aluminum frame and set to the same tilt angle equal to the Latitude of the installation site (29° South). The same load condition was initially used with all three PV modules, being three separate 39 Ohm 10 W fixed resistors in order to calibrate the system. The output power of these modules was then recorded and analyzed using LabVIEW software in conjunction with an Arduino board. Results were obtained over a four week period (October 2015) which indicated a coefficient of variation of 1.4%. This coefficient of variation is calculated using the standard deviation and mean of the collected data. This ensures the reliability and validity of subsequent electronic measurements when the three PV modules are connected to different load conditions, as described earlier.

TABLE 2: Load conditions

PV Module and load condition	Series resistors	Calculating current with Ohm's law
PV1 – 2 x 39 Ohm 10 W resistors in parallel	6 Ohm 10 W current sensing resistor	$I = \dfrac{16.5}{19.5 + 6}$ I_{max} = 0.647 A
PV2 – 2 x 4 W non-regulated LED lamps in parallel	6 Ohm 10 W current sensing resistor and a 10 Ohm 10 W series resistor per lamp	$I = \left[\dfrac{16.5 - 12}{10 + 6}\right] \times 2$ I_{max} = 0.537 A
PV2 – 2 x 5 W regulated LED lamps in parallel	6 Ohm 10 W current sensing resistor and a 10 Ohm 10 W series resistor per lamp	$I = \left[\dfrac{16.5 - 11.7}{10 + 6}\right] \times 2$ I_{max} = 0.6 A
PV3 – Solar controller, 12 Ah battery and 2 x 4 W non-regulated LED lamps in parallel	6 Ohm 10 W current sensing resistor	No calculation I_{max} = 0.610 A

Voltage readings are obtained from the Arduino board by using the analog read function in LabVIEW. The obtained values are multiplied by a predetermined factor for calibration and to compensate for any interface losses. This value is displayed on the front panel of the LabVIEW software that is visible on the screen. This value is then filtered by a Butterworth Filter that is used to filter out high frequency components that come from the Arduino's analog read circuit and any other high frequency noise present in the data logging system.

Voltage readings from the Arduino board represent PV module output voltages and currents. Current readings are obtained by measuring the voltage across a low value high power precision resistor (6 Ohm 10 W 1%). Voltage readings are obtained by using a standard voltage divider circuit (147 kΩ resistor in series with a 100 kΩ resistor). Multiplying the voltage and current readings within LaBVIEW yields a power reading in Watts that is written to a matrix for recording purposes. The total amount of power extracted per day from each PV module was then recorded in a singular text file for further analysis.

V. RESULTS AND DISCUSSION

Fig. II presents the LaBVIEW software interface which was developed by Hertzog and Swart to display electronic measurements obtained by the Arduino board. The following points have been highlighted:
- A: Date stamp highlighting the date (11 May 2016) when the data was recorded;

- B: Number of samples (4320) taken over the sample time (12 h);
- C: Total Wh recorded from PV module 3 for the specified day – In this case the total power is 53.92 Wh for the solar controller, which is 3.8 Wh more than the LED.
- D: Instantaneous power calculated for each sample for the fixed resistor (black line), the LEDs (red line) and the solar charger (blue line) – In this case it is 0 W, as the sample period has ended.
- E: Dip in power is visible for the fixed resistor load (black line) due to a pigeon which sat on the PV module.
- F: Start of the sample time is 06:00 with no solar radiation present – A rise in the current drawn from the PV modules is evident from 07:06.
- G: Current factors which are multiplied by the measured values from the Arduino board to obtain the actual measurements – 3 different factors exist due to the initial calibration of the system during October 2015.
- H: Blue line showing the voltage curve of PV module 3 connected to the solar charger.
- I: Red line showing the voltage curve of PV module 2 connected to the LED's.
- J: Black line showing the voltage curve of PV module 3 connected to the fixed resistors.

- K: Voltage factors which are multiplied by the measured values from the Arduino board to obtain the actual measurements – 3 different factors exist due to the initial calibration of the system during October 2015.

Fig. III indicates the total power extracted from the PV modules for November 2015 through February 2016 for different load conditions. During this period, the 4 W non-regulated LED lamp (red line) was used which resulted in a lower amount of power been extracted from the PV module as compared to the solar charger (green line). The 4 W non-regulated LED lamp even extracted less power than what the fixed load resistors (FLR) did (blue line). All power values below 30 W are considered to be the effect of cloud movement resulting in a disruption of direct beam radiation which is required for optimum output power from a PV module.

Fig. IV highlights the total power extracted from the PV modules for February 2016 through May 2016. Here the 4 W non-regulated LED was replaced with 2 x 5 W regulated LED lamps. This resulted in a larger amount of power been extracted from the PV module, as compared to the previous three months. In fact, the red line (2 x 5 W regulated LED lamps) now closely follows the green line (solar controller).
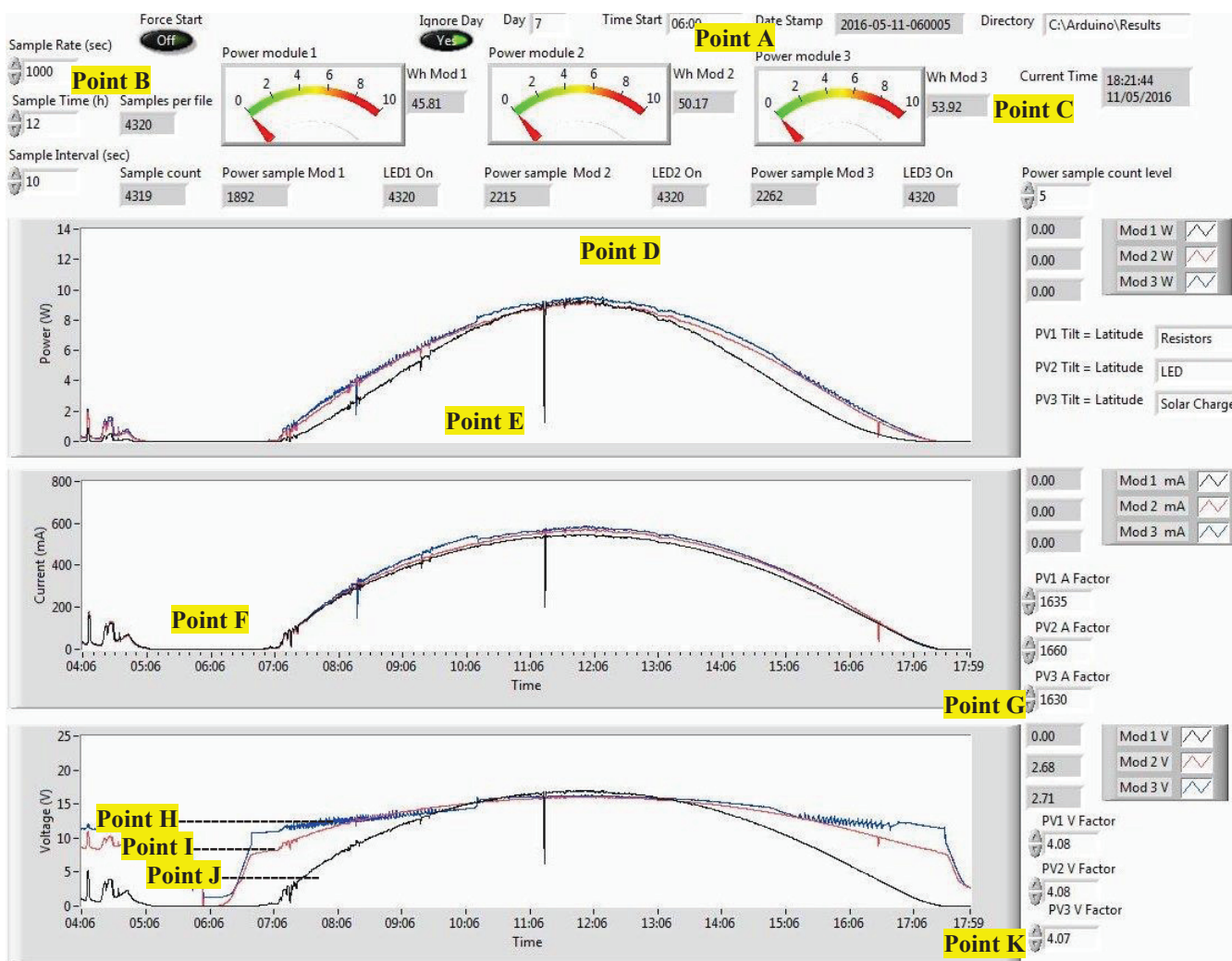

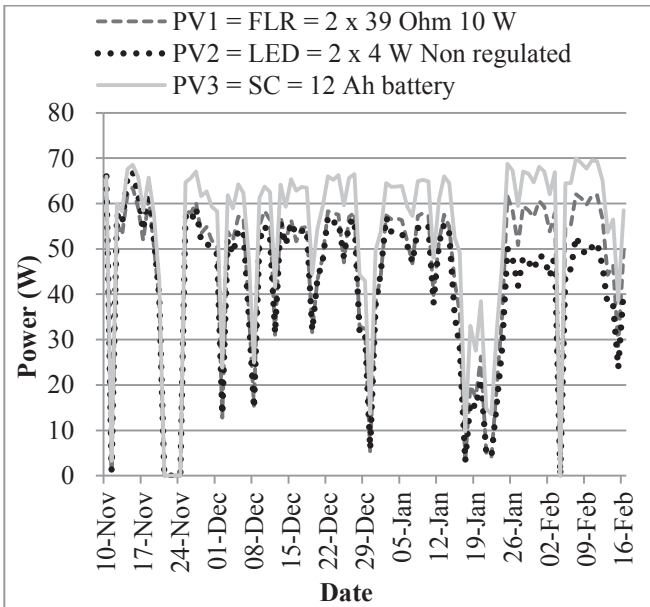Figure II: LaBVIEW interface showing results for 11 May 2016

Figure III: Total power extracted from the PV modules for November 2015 through February 2016 for different load conditions
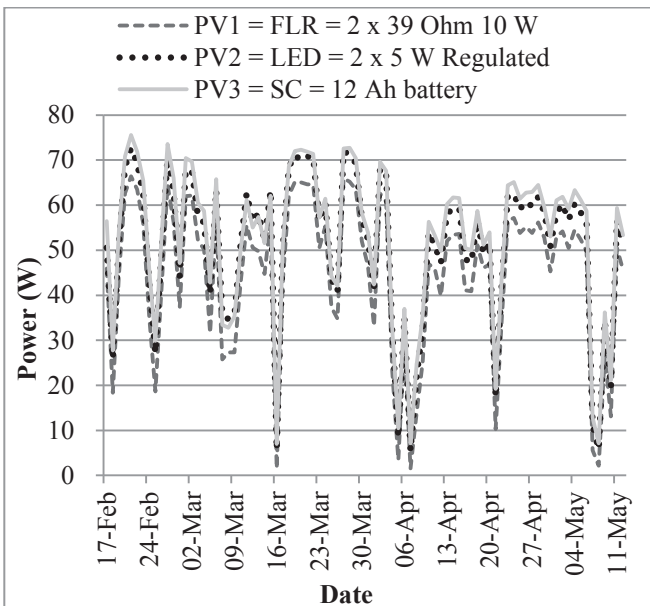

Figure IV: Total power extracted from the PV modules for February 2016 through May 2016 for different load conditions

Fig. V portrays the average power extracted from the three PV modules for November 2015 through May 2016, which is based on the data shown in Fig. IV and Fig V. The 2 x 4 W non-regulated LED lamps extracted, on average, 45 W per day, being the lowest of the three load conditions. However, the 2 x 5 W regulated LED lamps extracted 51 W per day, being only 2 W less than the solar charger. However, if the optimum output power is to be determined, then a solar controller is still the best choice as it extracted 56 W between November 2015 and February 2016, and then 53 W between February 2016 and May 2016. This decline in the power extracted by the solar charger is due to the annual solar radiation curve which has its peak in December and its trough in June.

Fig. VI shows the total power count for the three PV modules from November 2015 to February 2016 for the different load conditions, while Fig. VII illustrates this same data for the February 2016 to May 2016 period.
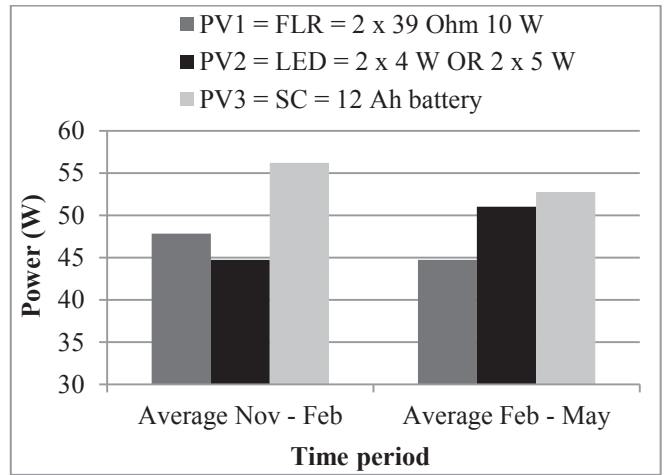

Figure V: Average power extracted from the three PV modules for November 2015 to February 2016 for different load conditions
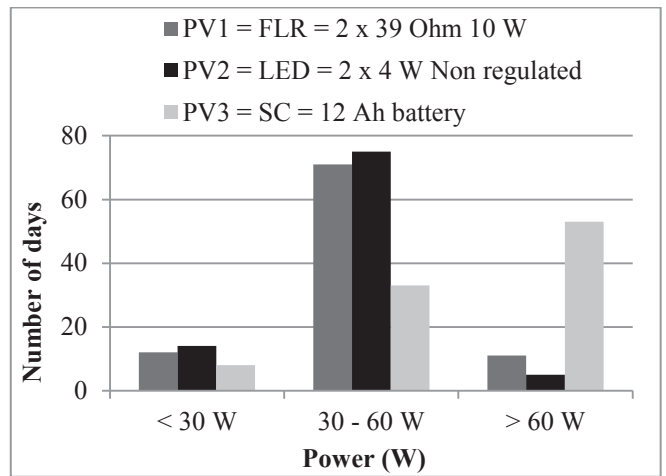

Figure VI: Total power counts for three PV modules from November 2015 to February 2016 for different load conditions (94 days in total)
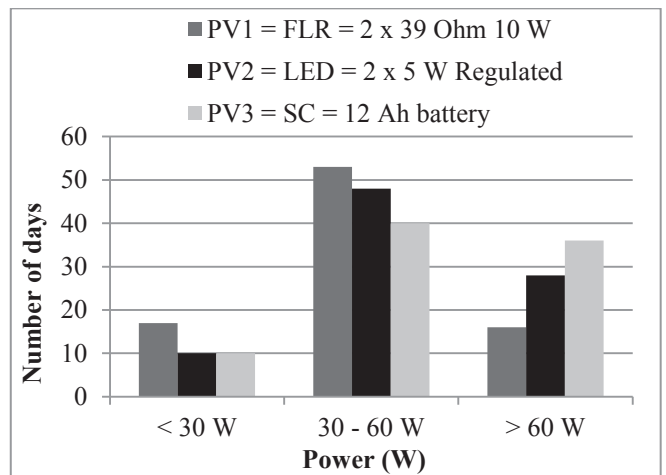

Figure VII: Total power counts for three PV modules from February 2016 to May 2016 for different load conditions (86 days in total)

Reviewing Fig. VI reveals that cloud conditions existed for approximately 10 days of the 94 days from November 2015 to February 2016. This equates well to recent weather reports and news broadcasts detailing the ongoing severe drought in the Free State region [19]. A similar scenario exists for the February 2016 to May 2016 time period, where cloud conditions were experienced for approximately 10 days out of the 86 days. This equates to a cloud coverage period of 11% for the total time period. Noteworthy though is the decline in the number of days in which 30 – 60 W was

extracted from PV module 2 for the 4 W and 5 W LED lamps. In Fig. VI, 75 days are observed while in Fig. VII only 48 days are observed. However, the number of days in which more than 60 W was extracted increased from 5 days in Fig. VI to 28 days in Fig. VII. This suggests that the performance of the 5 W regulated LED lamps is very closely matched to the performance of the solar controller.

This is substantiated by Fig. V (2 W difference between the two load conditions) and by Fig. II (blue and red power curve is very similar). The fundamental difference arises in the voltage curve of the solar controller and the 5 W regulated LED lamps, with the solar controller maintaining a higher PV module voltage than does the LED lamps. The fixed load resistor, shown in Fig. II, has the worst performance, with a lower voltage value before 09:00 and after 15:00. Resistors can be connected in various networks to acts as a voltage dropper, voltage divider, or current limiter [20]. However, it can severely reduce the source voltage if it is attempting to draw more current than what is available or it may draw less current than what is available.

VI. CONCLUSIONS

The purpose of this paper was to present empirical evidence contrasting the performance of three identical 10 W PV modules connected to three unique separate loads in order to establish an economic viable load when considering similar output power results. The theoretical analysis highlighted that the local cost for a 15A solar controller is R180, while 2 x 5 W regulated LED lamps may cost less than R90. Two fixed load resistors (39 Ohm 10 W) are the cheapest option at around R10 each.

The experimental setup revealed that only one variable is different between three identical PV systems, being the load conditions. Data from these three PV systems was recorded from November 2016 through May 2016. Results indicate that a solar controller extracts more power from a PV module (on average 3.9% more power), as compared to a regulated LED and a fixed load resistor. The load resistor extracts approximately 16.7% less power than a solar controller. However, the 2 x 5 W regulated LED lamps follows a profile similar to that of the solar controller, drawing on average 2 W less per day.

It is recommended that regulated LED lamps be closely matched to the maximum power point voltage and current of a specific PV module. This may be done by determining the total series resistance that should be used in conjunction with the LED lamp to draw a current closely matched to the maximum power point current of the PV module. This will enable its use as a viable load, being closely matched to the performance of an appropriately selected solar controller.

Future research may consider using this practical setup with larger sized PV modules (20 W and 50 W), matching the number of regulated LED lamps to their output power. Obtaining additional results from this practical setup for winter and spring months may further cement the usefulness of regulated LED lamps as an economic viable load for experimental purposes involving small scale PV modules. Proven advantages include lower costs (less than 50% of the price for a solar controller) and its close emulation of a solar controller's performance. This will adhere to the fundamental universal principle that one cannot use more power than what one produces, but can produce an amount of power which is very close to the maximum extractable power from a PV module.

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