Performance monitoring of a photovoltaic thermal collector

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**Abstract**. Photovoltaic (PV) modules convert around 15% of incoming solar radiation into electrical energy. This implies that a significant percentage of the remaining radiation is absorbed as heat or reflected. PV modules are known to operate at temperatures as high as 60°C when irradiance levels increase above 900 W/m2, which detracts from the standard test condition (STC) rated power of the modules. It is therefore worth investigating how the absorbed heat can be dissipated in a constructive manner. This study thus aims at developing a mechanism to exchange the heat absorbed by PV modules with a coolant such as water, turning the PV modules essentially into a thermal collector in addition to generating electricity. This paper presents the design and performance monitoring of a photovoltaic (PV) module when used as a thermal collector for heating water. The photovoltaic thermal system (PTS) installed at the University of Fort Hare comprised of a 94-litre system. The PV modules used were 80 W polycrystalline silicon modules, each with STC conversion efficiency of 11%. Findings indicated that the PV module in the PTS operated at lower temperatures resulting in higher efficiencies. The monthly energy saving efficiency of the PTS was found to be approximately 61%. This paper presents the performance monitoring of the PTS as compared to the equivalent PV module for five months.

1 Introduction

In South Africa 95% of its primary energy mix consists of 77% coal, 13% oil and 5% natural gas and the remainder 5% is contributed from biomass and renewable energy [1]. When burnt, the fossil fuels produce carbon dioxide, nitrogen dioxide and sulphur dioxide. These gases contribute negatively towards the environment by causing global warming. Fossil and nuclear fuels are unsustainable and it is imperative to reduce our daily reliance on them. Renewable energy resources are however sustainable and can be used continuously without notable negative environmental impact [2]. This signifies the need for renewable energy resources.

Photovoltaic (PV) systems are cleaner means of electricity production, no emissions during electricity production, no noise from the PV generators and are environmentally friendly. PV systems have been used mainly in outlying areas not connected to the electricity utility grid. However silicon photovoltaic modules only convert around 15% of incoming solar radiation and the rest is lost mainly as heat and through reflection. Therefore it is worth investigating on how the lost heat can be utilised. Real data need to be used to determine the performance of the PV modules with respect to electricity and warm water production. In this paper the performance analysis of the system was carried out for the months of September 2011 to January 2012.

* 1. *Theoretical Background*

The power from a PV module is determined using the relationship:

(1)

Where: *P*max is the maximum power; *Vm* is the maximum voltage; *Im* is the maximum current. Energy produced is generally given by the relationship:

(2)

The time can be the day’s length, month or year. The day’s length in terms of hours is given according to equation 3, [3].

(3)

Where; *Ø* = the angle of latitude; *δ* is the declination angle and can be calculated from:

(4)

Where: *n* is the number of the day in the year. The total energy produced per m2 of the solar module for one day can be estimated from the relationship:

(5)

To characterise the performance of the PV system the International standard IEC 61724 in [4] was used to calculate the performance ratio for the two modules M1 and M2 (PTS) each day of the month. The relationships used were:

; ; and (6)

Where: *Yf* is the final yield; *E* is the energy produced by the PV system; *Po* is the installed/rated peak power; *Yr* is the reference yield; *H* is the plane of array irradiance; and *G* is the STC irradiance.

* 1. ***Efficiency of a cell***

The efficiency of a cell is defined as the ratio of energy output from the solar cell to input energy from the sun. This has been found to depend on the spectrum and intensity of the incident sunlight as well as the temperature of the solar cell [5]. The electric conversion efficiency of a solar cell is determined as the fraction of incident power, which is converted to electricity and is defined as:

(7)

Where: *Acell* is the area of the cell or module (m2)

1. Experimental Method

The system used for the study consisted of two SW80 PV modules each with an area of 0.719 m2 and 36 cells in series connection. One module, M1 was naturally cooled by air and used as a control and the other M2 was cooled by water in direct contact with the back of the module. Table 1 shows the two modules’ rated performance under STC (1000W/m2, 25°C, AM 1.5).

|  |  |  |  |
| --- | --- | --- | --- |
| *Table1*: The SW80 Poly/RIA corresponding rated STC values | | | |
| **Quantity** | **Units** | **STC Value** |
| Short circuit current, *Isc* | A | 4.42 |
| Open circuit voltage, *Voc* | V | 21.50 |
| Maximum current, *Imax* | A | 4.48 |
| Maximum voltage, *Vmax* | V | 17.90 |
| Maximum power, *Pmax* | W | 80.19 |
| Efficiency, *η* | % | 11.14 |

The experiment was carried out on a north facing test rig at tilt angle of 32.75°, the latitude of Alice, South Africa. The modules were connected to the I/V low cost system developed at the Fort Hare Institute of Technology [6], and to the Sunsaver MPPT (maximum power point tracking) charge controller. The charge controller was connected through a Morningstar PC Meterbus to a personal computer for data logging. Data logged from the controller were module current and voltage output as well as load current and voltage and battery voltage, all measured by the sunsaver MPPT. The storage tank was placed at a height of 30 cm to enable the thermosyphon effect. Figures 1 and 2 illustrate the photos of M1 and M2 on a test rig and that of data acquisition system (DAS), respectively. The schematic diagram in figure 3 shows the connection setup of the system.

In the setup the interconnection of modules and the charge controllers as well as the I/V tracer are shown. The data was automatically recorded at a 30-minute interval from 06h00 to 19h00. The irradiance, wind speed and temperatures were all recorded every 10 minutes for 24 hours over the five-month period.

|  |  |  |
| --- | --- | --- |
| M1  M2  **Storage Tank**  **Pyranometer** |  |  |
| *Figure 1*: M1 and M2 on N-facing test rig |  | *Figure 2*: Photo of Data Acquisition system |



*Figure 3*: Diagrammatic connection setup of the system

**3 Results and Discussion**

***3.1 Electrical***

Table 2 lists the mean daily values for each month of ambient temperature, module temperatures, irradiance and energy received on the plane-of-array (POA).

*Table 2*: Mean daily values of ambient temperature, modules temperatures, irradiance and POA energy for each month.

|  |  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Month** | ***Tamb***  **(°C)** | ***TM1***  **(°C)** | ***M1***  **(%)** | ***TM2***  **(°C)** | ***M2***  **(%)** | ***H***  **(W/m2)** | | ***E***  **(kWh/m2)** | |
| September | 19.22 | 30.19 | 9.47 | 22.70 | 9.80 | 548.60 | 6.51 | |
| October | 20.63 | 30.44 | 7.34 | 23.82 | 9.83 | 441.13 | 5.69 | |
| November | 19.97 | 28.61 | 9.42 | 24.08 | 9.33 | 418.83 | 5.75 | |
| December | 22.54 | 24.16 | 8.29 | 27.17 | 8.23 | 380.30 | 5.37 | |
| January | 26.48 | 31.84 | 8.91 | 32.00 | 8.00 | 456.41 | 6.34 | |

Figure 4 illustrates the parameters listed in table 2.

*Figure 4*: Monthly variation of temperature, efficiency and irradiance

The irradiance in the month of September was 31% more as compared to the month of December. This was attributed to rains and cloud overcast noted in the months of November and December as compared to the other months. In the months of September and October the back of module temperatures for the directly water-cooled module (M2) indicated a cooler back of module temperatures as compared to M1.

In order to determine the performance ratio (*PR*) of the modules equation (6) was used as illustrated in figure 5. The *PR* represented includes *PR* calculated using the rated efficiency for the SW80 module and the *PR* calculated using the determined efficiency for each module every month. To explain the trends in figure 5, the percentage differences between *PR* for modules M1 and M2, and that between the modules and rated values are as shown in figure 6.

*Figure 5*: Performance ratio of the modules *Figure 6*: %*diff* between Rated and modules M1 and M2, and between M2 and M1.

From figure 6 it can be noted that M2 out performed M1 in the months of September (by 3.4%) and October (by 25.3%). However in the months of November and December M1 out performed M2 by 1.0% and 0.7% respectively. The worst performance of M2 was noted in January with M1 out performing M2 by 11.3%. In January the average back of module temperature for both modules were 32°C.

The average monthly maximum power output of the modules were determined around solar noon and are shown in Figure 7 below.

*Figure 7*: Normalised maximum power of the two modules

From September to October there was a 28% drop in power output of M1 with no change in the power output of M2. This constitutes the 25.3% difference between M2 and M1 as depicted in figure 6. Although the back-of-modules temperatures are constant over these two, the back-of-module temperature for M2 was significantly higher than the actual cell temperature, due to the cooling effect of the water, which is in direct contact with the back surface of the module. Both modules had a local maximum in November, which generally had clear skies. The observed decrease in performance (~19%) November to December may be attributed to the fact that during these summer months, the irradiance may be high at solar noon with cloud cover and showers in the afternoon. The lower average daily irradiance levels in figure 4 support this.

***3.2 Thermal Response***

Thermosyphon systems are affected by variations in solar radiation, ambient temperatures, wind conditions, connecting pipe sizes and design parameters [7]. The daily thermal efficiency of the system can be found using the relationship [7],

(10)

Where *m*, *Cp*, *Tf*, *Ti*, *Ac*, *H* are the total fluid mass in the thermosyphon system, heat capacity, final and input temperatures in the storage tank, collecting area of the PV module, and the daily total incident solar radiation on the collector surface from 06h00 to 16h00.

The overall performance of the PTS can be determined by finding the total efficiency given by equation (12) and energy saving efficiency (13)

(12)

Where , , are electrical efficiency, thermal efficiency of the PTS. The energy saving efficiency of PTS is given by equation (13).

(13)

Where 0.38 is the electric efficiency of a thermal power station used to give the energy saving of the PTS [8]. The average monthly thermal efficiencies of the PTS are listed on table 3.

*Table 3*:Average monthly electrical and thermal efficiencies

|  |  |  |  |  |  |  |  |  |
| --- | --- | --- | --- | --- | --- | --- | --- | --- |
| **Month** | **(°C)** | **(°C)** | ***∆T***  **(°C)** | **(°C)** | ***H* (MJ/m2)** | ***th***  **(%)** | ***e***  **(%)** | ***s***  **(%)** |
| September | 10.89 | 28.64 | 17.75 | 19.22 | 20.88 | 46 | 9.80 | 71.79 |
| October | 12.66 | 25.39 | 12.73 | 20.63 | 18.55 | 41 | 9.83 | 66.92 |
| November | 16.62 | 27.80 | 11.18 | 19.97 | 18.84 | 31 | 9.33 | 55.55 |
| December | 19.70 | 30.07 | 10.37 | 22.54 | 16.62 | 33 | 8.23 | 54.66 |
| January | 26.92 | 39.08 | 12.16 | 26.48 | 18.89 | 35 | 8.00 | 56.05 |
| **Average** |  | | | | | | | **60.99** |

From table 3 it can be noted that the PTS had a higher thermal efficiency in September and October as compared to other remaining months. The likely reason for this was that in the months of September and October it was cooler as compared to other months. The monthly energy saving efficiency of such a system was found to be approximately 61%.

**4 Conclusions**

Higher electrical and thermal efficiency values were obtained from the PTS in the months of September and October as compared to remaining months under consideration. The PTS (M2) also displayed higher *PR* ranging from 1.00 to 1.23, while *PR* for M1 varied from 0.92 to 1.18. The average monthly energy saving efficiency of the PTS was found to be approximately 61%.

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