Enhancement of Solar Photovoltaic (PV) Power Generation Efficiency Using Thermoelectric Generator (TEG) Modules

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Abstract—Solar photovoltaic power generation has gained wide popularity worldwide due to its renewable nature. However, high temperature conditions compromise the power generation by a substantial margin. This study was intended to investigate the effects of temperature and how these effects could be reduced using a cooling plate mounted on the backside of the PV module connected to a thermoelectric generator (TEG). Thermoelectric generators generate electricity using a temperature gradient that is created by the PV module back plate. Under varying irradiance, weather and temperature conditions the PV + TEG arrangement was used to generate power. In this set up, a 13Wp Polycrystalline 12V PV module and series connected TEG modules were monitored. The TEG modules type SP1848-271455SA, 40mm x 40mm x 3.5mm were series connected and mounted under the PV module sandwiching a graphite thermal conduction pad. An aluminium honeycomb (BPE) Alucore cooling plate was used to clamp the PV module to the TEG and then made to float in a water tank. A similar 13Wp PV module, without cooling, was monitored under the same conditions. The results showed average open circuit voltage gain of +3.5% and D.C power gain of +6% on the cooled PV+TEG module. The TEG had an average open circuit voltage of 1.63 volts with a peak of 3.6volts under high irradiance conditions. When the power generated from the TEG is taken into consideration, a much higher power gain could be achieved.

Keywords: *Thermoelectric generator, Photovoltaic, Cooling Module, Figure of merit Zt*

1.0 Introduction

High Photovoltaic (PV) module temperatures have far-reaching adverse effects on the power generation potential of solar PV modules. Considering that solar irradiation is not constant due to varying daily weather conditions, it is prudent to improve the power generation output by varying the physical conditions on the PV module. These include the temperature and the angle of tilt of the module. The main parameters of a PV module are the current and the voltage. Both are proportional to the solar irradiance. However, the voltage is inversely proportional to the module temperature. Cooling of PV modules therefore could result into more power generation by maintaining the output voltage of the PV near constant for varying temperatures.

The elevated module temperature could be exploited by using it to create a temperature gradient that is suitable for power generation in a Thermoelectric Generator (TEG) module. Thermoelectric generators are metals that are connected to form a p-n junction to generate electricity using the Seebeck phenomenon [1]. Thermoelectric generators are formed using materials that have high electric conductivity and low thermal conductivity that is known as the Figure of merit (Zt). Most of the materials commonly used have a figure of merit (Zt) ranging between 1 and 1.5. Examples include Bismuth telluride (Bi_2Te_3) Silicon germanium (SiGe) and Lead telluride (PbTe) [2].

2.0 PV and TEG Power Generation Principles

Photovoltaic modules generate electricity from the solar irradiance falling on them. The voltage/current characteristic curve of a PV module is mostly linear at low voltages up to about 15volts and becomes inverted -exponential at higher voltages as it approaches the open circuit voltage (Voc) [3]

The voltage output of a PV module at any ambient temperature can be estimated as;

$$V_{oc}(mod) = Temp\ coeff \times (T_{STC}[°C] - T(mod)[°C]) + V_{oc}(rated)[V] \qquad (1)$$

Where,

Voc is the module open circuit voltage during measurement,

Temp coeff is the temperature coefficient for the polycrystalline module type (0.12V/^{0}C [4],

T_{STC} is the temperature at standard test conditions,

T(mod) is the module temperature during the time of measurement,

Voc (rated) is the the rated factory stated open circuit voltage at STC

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Table 1: The Solar PV Module Specifications at STC

PARAMETER	VALUE
P_{MPP}	13Wp
I_{MPP}	0.78A DC
V_{MPP}	18 VDC
V_{OC}	21.6VDC
I_{SC}	0.8 ADC
M_{SV}	715 VDC

On the other hand, the TEG relies on a temperature gradient between its two faces to generate electrical power. The higher the Zt of the material the higher the electrical power it shall be able to generate [5].

Zt is given as = $\left[\frac{(\alpha^2\sigma)}{k} x\ T\right]$ (2)

Where σ is the electrical conductivity, α is the Seebeck coefficient and k is the thermal conductivity of the material and T is the absolute temperature.

The voltage generated by a TEG material is given by [5]

$V = S^* \Delta t$ (3)

Where S is the Seebeck coefficient and Δt is Th - Tc

The TEG specification in Table 2 [6]

Table 2: TEG Specifications

TH –TC = ΔT	Voc (Volts)	I (mA)
20^0C	0.97	225
40^0C	1.8	368
60^0C	2.4	469
80^0C	3.6	558
100^0C	4.8	669

3.0 Data Collection set-ups

Two set-ups were made to collect the data for the study. One system was set up on the rooftop of the Institute of Energy and Environmental Technology (IEET-JKUAT) and the second one was setup at the solar PV workshop within the precincts of the institute.

3.1 Set-up for Irradiance and temperature measuments

The setup for collection of continuous data was done on the roof top for convenience of data collection and to avoid any chances of shading on the pyranometer used.

Figure 1: Daily irradiance measurement on the roof using a Pyranometer (Set up 1)

Table 3*: Devices installed for Temperature and Irradiance* data collection in system 1

NAME	DESCRIPTION
TEMPERATURE SENSOR	PT100
SOLAR PV MODULE	Polycrystalline -13Wp
PYRANOMETER	CMP 3
DATA LOGGER	COMBILOG 1022

Both systems were set up using the module type whose specifications are shown in Table 1.

3.2 Characterization of the 13Wp PV Modules

Before the setup 2 was done to measure the open circuit voltage of the PV modules, Load voltage, load current, surface temperature and the cooling water temperature, the selected modules were first checked against their technical specifications and their Voc measured under same conditions so as to characterise and compare them. This test was also done to identify any major differences on the open circuit voltage output before the temperature effects test began. The two modules were laid flat on a wooden board considering that the site of testing (Juja) is only 1.16^0 South of the equator [7]. The testing was done for 240 minutes when the weather was relatively clear as in Figure 2.

Figure 2: Characterisation of the 13Wp PV Modules

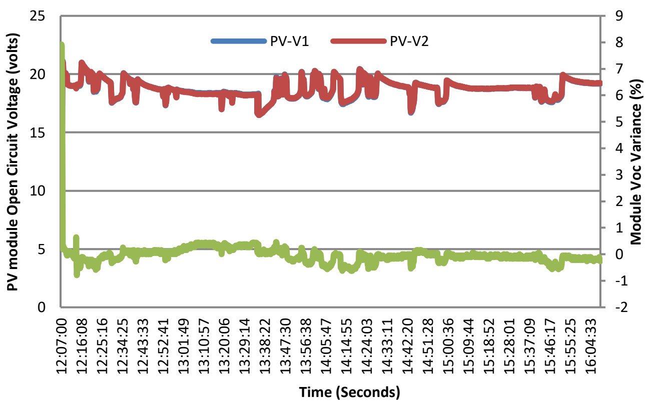

Figure 3: 13W$_p$ PV Module Characterisation

3.3 Set-up 2

Measurement set-up 2 was made outside the solar PV workshop convenient enough to access the data logging equipment from outside. The setup was for collecting PV module open-circuit voltage, short-circuit current, load voltage, and load current. The other data collected was open circuit voltage for the thermoelectric generator, water temperature, spot irradiance and spot module temperature.

Table 4*: Major Equipment installed for Set-up 2* data collection system.

NAME	DESCRIPTION
UN-COOLED PV MODULE	Poly-13Wp
COOLED PV MODULE	Poly-13Wp
DATA STORAGE	Laptop-Lenovo
DATA LOGGER	KEYENCE-NR500
TEMPERATURE METER	AD5615
IRRADIANCE METER	TENMARS-208
MULTIMETERS	Hioki 3287 RMS

Figure 4: Set up number 2 at the solar PV workshop

The capacity of the water reservoir steel tank was 0.4392 cubic meters.

4.0 Data collection and Analysis

Data was collected from setup 1 and setup 2 simultaneously. However, the setup 2 data was collected only when solar irradiation was available during the day and in intervals of two to three hours enough for analysis while the setup1 data was continuous 24hours a day unless a deliberate interruption was necessary.

4.1 Data Collection Setup 1

The data collected in setup 1 was mostly module surface temperature and daily horizontal irradiance. This data was collected to observe the effects of direct irradiance on module surface temperature and also observe daily horizontal irradiation potential for the site (IEET-JKUAT) 1.16^0 south of the Equator.

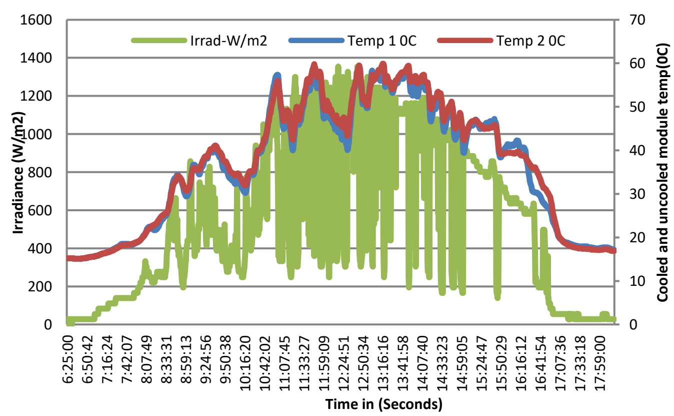

Figure 5: PV Module surface temperature and daily Irradiance

The day under observation had an irradiation energy potential of 6.32kWh/m^2 of as observed. The temperature difference between the cooled and uncooled modules was very small with an average of 1.5% due to the prevailing weather conditions in Figure 5.

4.2 Data collection for setup 2

The data collected in setup 2 was mainly open circuit voltage (Voc) for the cooled and uncooled module to observe the difference in Voc that is caused by temperature effects. The modules were connected open circuit to the KEYENCE NR500 logging device to collect this data as in Figure 4. At the same time, the TEG open circuit voltage was also monitored.

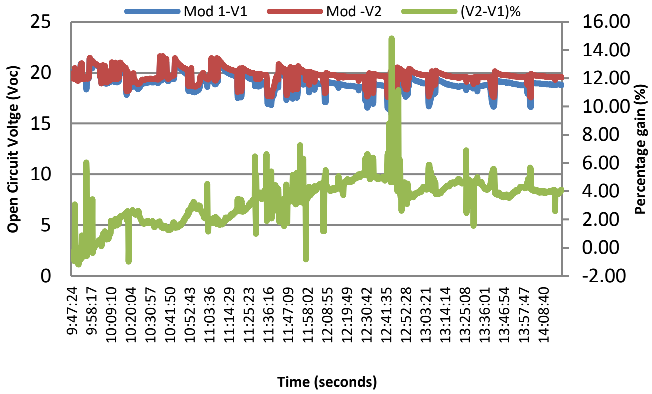

Figure 6: PV Module Open Circuit Voltage variation

The difference in Voc between the two modules was an average of 3.5% for the 13Wp module as in Figure 6. It is expected that this Voc difference would be considerable in a PV system of many series connected modules.

The other data collected in this setup was power data for the two identical modules. Both the modules were connected across a purely resistive load designed equivalent to their maximum power output load on their voltage-current characteristic curve. This was done to observe the effect of temperature on the power output of the identical modules under cooled and uncooled conditions.

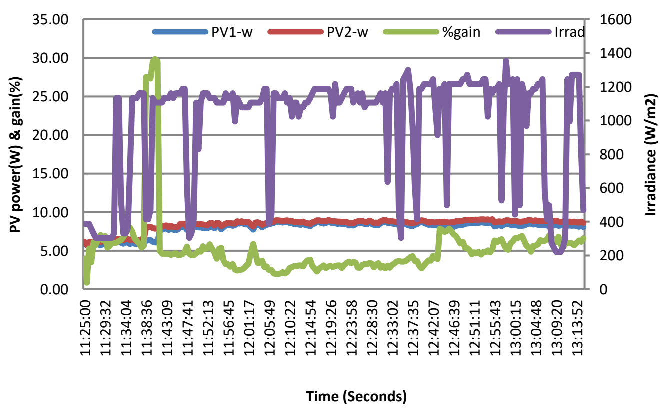

Figure 7: PV Power and Irradiance variations

In this measurement, the cooled module generated higher power output compared to the uncooled module with an average power gain of 5.4%. For the period taken during the measurement Figure 7, the cooled module harvested some 15.38Wh compared to the uncooled one of 14.64Wh with available energy of 99.61Wh

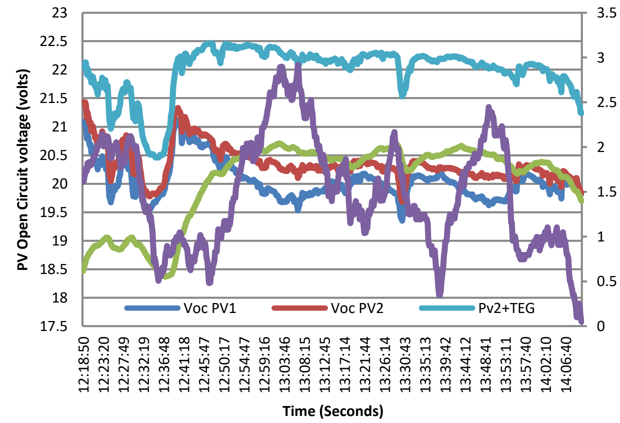

Figure 8: PV and TEG Open Circuit Voltage

In the measurement graphically presented in Figure 8, the test was done for 108 minutes when there was high irradiance. The uncooled module had an average Voc of 20.09V while the cooled module had an average Voc of 20.39. The TEG had an average Voc of 1.63V and the cooled PV module + TEG had average 22.02V. The percentage voltage gain was averaged at 1.5% for the 13Wp PV modules.

5.0 Results

The results obtained in both setups show considerable voltage and power gain with average values varying between 3.5% and 5% for the open circuit voltage and 5 and 7 % for the power gain. The energy generated for the periods observed was higher for the cooled module with an average percentage of 5.05% for the 13Wp polycrystalline module used. The TEG Voc was considerable with an average of 1.63V for the period tested. While the cooled PV module displayed a consistent higher voltage more than the uncooled PV maintaining an average percentage of +1.5%.

6.0 Conclusions

In this paper two setups for measurement were made and data was collected and analyzed to study the effects of temperature reduction on solar PV modules. The voltage output from TEG modules operating under the PV temperature gradient was observed. The open circuit voltage of the cooled PV module was found to be higher than that of the uncooled module. The energy gain averaged 5.5% for the 13Wp module. Considering that the TEG modules can be mounted under the PV modules to absorb the heat and generate electrical power, the benefits shall be considerable if the extra power generated by the TEG is quantified.

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