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Feasibility Study on Thermoelectric Conversion to Improve Photovoltaic Operation

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Abstract

Thermoelectrics (TE) is an emerging technology with a wide range of potential applications namely recapturing energy lost as wasted heat from burning fossil fuels as well as serving as a cooling agent. One viable application is to integrate thermoelectric devices with photovoltaic (PV) modules that suffer from performance issues because of heat. This study proposes a model where the TE device can help lower the temperature of the PV modules which will optimize its performance through an increase in generated output. The same device can also increase the total output power from the combined PV-TE system when the TE acts as a generator. The PV-TE system was simulated using Matlab software and results show that there is potential in using TE technology as coolant and generator improve the performance of the PV device. Experiments and actual deployment also reveal an improved output for the combined PV-TE system.

Keywords: *Thermoelectric cooling/generator, Photovoltaic module, conversion efficiency, PV-TE system, Seebeck coefficient, temperature difference*

1. Introduction

Fossil fuel energy has been constantly scrutinized for its negative impact on the environment. Not only does it harm the environment with its carbon emissions and depletion of natural resources that are running out fast, it is not as efficient as it seems. When power plants burn fossil fuel to produce electricity, only a fraction (roughly one-third) of it is converted to useful energy while the rest of it is lost as waste heat (Jones, 2012). Efforts have been made to recover this untapped source of energy and one of the best ways to achieve this is through thermoelectric technology.

Thermoelectrics (TE) uses a temperature gradient to generate electricity. This is made possible by two different semiconductor materials coupled together, arranged electrically in series and thermally in parallel (Rowe, 2006). When a temperature gradient is applied to it, current flows through the system resulting in a voltage difference. This phenomenon is called the Seebeck Effect. When voltage is applied instead, a temperature difference occurs which results in heating on one end and cooling on the other. This is called the Peltier Effect. A third phenomenon occurs called the Thomson Effect that plays a negligible role in the operation of practical thermoelectric modules (Tellurex, 2010).

Thermoelectrics is still a niche technology that is not widely used in the market due to the poor energy conversion efficiency of its devices. Given the right application however, its unique characteristics could prove beneficial. The most popular of these applications is cooling and refrigeration owing to its precise temperature control.

While thermoelectrics is not a well-known category in the field of renewable energy, photovoltaic (PV) technology is its most prominent. Unfortunately it is also susceptible to issues of conversion efficiency. Heating of the photovoltaic PV modules above standard conditions causes performance issues where the device suffers losses in performance efficiency due to high temperature due to high irradiance conditions which also lead to cell degradation (Najafi and Woodbury, 2012). Temperature affects the speed of electrons

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flowing through a circuit. The lower the temperature, the lower the resistance in the circuit, the better the performance (Teach Engineering, 2015). Increasing the temperature on the other hand will reduce the band gap of the semiconductors in the PV cells leading to more energy of the electrons which is not ideal in order to break the bond (PV Education, 2015). Cooling the solar cells allows them to function at a higher efficiency and produce more power. Increasing conversion efficiency of any alternative power generation system is crucial because conventional means of producing energy is cheaper.

A feasibility study on a photovoltaic-thermoelectric hybrid system was conducted by Van Sark where an idealized model was able to calculate the employment of present day thermoelectric materials that could lead to efficiency enhancements of up to 23% for roof integrated PV-TE modules. Instead of simple module cooling methods, the study proposed utilizing the thermal waste by attaching thermoelectric converters to the back of the PV modules resulting in a PV-TE hybrid module (Van Sark, 2011). A more comprehensive model of the combined system of the PVT-TEG was developed and simulated by Najafi and Woodbury (2013) where the TE Generator is also employed to convert the heat generated by photovoltaic or thermal collectors into electricity. The model illustrated a very detailed heat transfer process where the TE modules convert the temperature gradient to electricity and generate additional power from the excess heat which is an improvement to the overall performance of the system. Another approach by Park et al. (2013) focused on optimal hybridization between the PV and TE devices by using "full spectrum solar energy" by means of lossless coupling between the devices in hopes of reaching the ideal for efficient harnessing of solar energy. These studies have indicated that attaching a TE device to a PV device has improved the conversion efficiency and power output of the photovoltaic module.

The use of thermoelectric conversion as a strategy to mitigate the issue has been examined where a PV-TE hybrid utilizes thermal waste. Thermoelectric devices make ideal cooling agents because they are solid-state materials that are reliable, durable and compact, with zero maintenance, no noise and no mechanical parts (Teach Engineering, 2015). This paper proposes integrating TE devices, which actively use heat, to PV modules as its cooling mechanism. PV-TE systems have been explored in the past however the type of integration that is modeled in this study attempts to make use of the TE device's two functions albeit not in a simultaneous manner.

2. Designing theoretical models for feasibility testing

2.1. Visualized Model of Proposed PV-TE System

A layout of the design of the PV-TE model is shown in Fig.1 where a solar PV module was deployed. Data of the PV without any TE attachments was first collected and acted as the control. The data output was examined in contrast with PV data of the setup installed with TE devices.

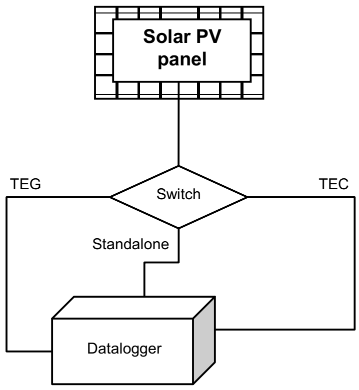

Fig. 1 Layout design of model to study the feasibility of the PV-TE System

The TE system alternated between energy harvesting mode and cooling mode as seen in Fig. 2. Data of the PV with TE attachments in generator or cooling mode were collected and compared with PV-only set of data. Note that the TE device as a generator is an accepted form of cooling and has been an examined approach by many previous authors (Van Sark, 2011; Najafi and Woodbury, 2013; Park et al., 2013) as it absorbs heat from the PV modules so it can convert it to energy. This can be seen as a passive form of cooling, whereas when the TE device is in its actual cooling mode, this would be an active or forced form of cooling.

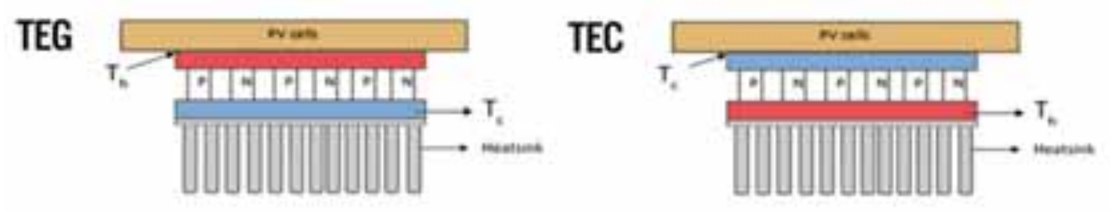

Fig. 2 **Schematic of the PV-TE Section with (left diagram) in *generator* mode; and (right diagram) in *cooling* mode**

As the TE system shifted from generator to coolant, the thermal equilibrium between the ambient air and PV was observed. The system remained a generator during parts of the day as it is judged to be more effective. It switched to a coolant during times it was seen more effective as such.

2.2. Mathematical Modeling

Typical TE module equations are described in existing literature (Diaconescu and Grigorescu, 2009) where the generator output voltage is given as follows:

$$V = S_M \Delta T = I(R_M R_L) \quad \text{(Eq. 1)}$$

Where S_M is the device's Seebeck coefficient and $\Delta T = T_H - T_C$, I is the current through the load, R_M is the averaged module resistance and R_L is the load resistance. The current I through the load is given in Eq. (2) where N_S is the number of TE modules connected in series, and N_P is the number of TE modules connected in parallel.

$$I = \frac{N_S S_M \Delta T}{\left(\frac{N_S R_M}{N_P}\right) + R_L} \quad \text{(Eq. 2)}$$

The general expression for generator output power P is typically given as the product of voltage V and current I but can also be calculated as seen in Eq. (3) derived from Eqs. (1-2) where N_T is the number of TE modules used and is calculated as $N_T = N_S \times N_P$.

$$P_{TE} = VI = R_L\left(\frac{S_M \Delta T}{R_M + R_L}\right)^2 = \left(\frac{N_T (S_M \Delta T)^2}{4R_M}\right) \quad \text{(Eq. 3)}$$

The output power of the PV-TE system is the total of the power of the TE derived from Eq. (3) and output power of the PV derived from collected experimental data using the equation for power at the maximum point as given in Eq. (5) where E is the irradiance and A is the area of the PV module.

$$P_{PVTE} = P_{PV} + P_{TE} \quad \text{(Eq. 4)}$$

$$P_{PV} = \frac{P_{\max}}{EA} \quad \text{(Eq. 5)}$$

In thermoelectric cooling, precise temperature control is its strongest feature. The Peltier effect allows for a cold surface to cool to a temperature T_C and a hot surface to cool to a temperature T_H. This is made possible by the given equation described by Khattab et al. (2005):

$$V = S_M (T_H - T_C) + R_M I \quad \text{(Eq. 6)}$$

3. Simulation and Hardware Design

3.1. Physical model and assumptions

The TE device used for the study is the commercially available TEC12706. The device is a single stage module that contains 127 pairs of thermoelectric p-type and n-type elements made of Bismuth Telluride with two terminals in dissimilar colors (black and red). This device has interchangeable polarity. The basic performance parameters of this TE device are listed in Table 1. (Ferrotec Corporation, 2014)

Table 1: Performance Parameters of the TEC12706

Parameter	Value
Dimensions	40mm x 40mm x 3.8mm
Maximum Operating Temperature, T_{max}	90 ~ 100 °C
Maximum Temperature Difference, ΔT_{max}	70 °C
Maximum Operating Voltage, V_{max}	15 V
Maximum Current, I_{max}	6 A
Maximum Cooling Power, Q_{max}	50 W
Resistance, R	1.98 Ω

Prior to performing simulations, the following assumptions are adopted to simplify the problem:

- The solar TEG is in steady-state.
- The configurations of the p-type and n-type elements are identical.
- The thermoelectric elements are connected electrically in series and thermally in parallel.
- The whole system is in a vacuum environment, so the heat loss due to heat convection is neglected. (Chen et al., 2013)
- The heat sink is not included in the computations, and the ambient temperature is assumed to be a constant specified by the weather report for that day.

The TE device is characterized by three parameters that are most vital in modeling its capabilities: namely, the module Seebeck coefficient, resistance and thermal conductivity. These properties can be approximated through manufacturer data. (Ferrotec Corporation, 2014)

Table 2: Performance Parameters of the GP005PA PV Module

Parameter	Value
Dimensions	190mm x 290mm x 15mm
Peak Power, P_{max}	5 W
Maximum Power Voltage, V_{mp}	18.29 V
Open Circuit Voltage, V_{oc}	22 V
Maximum Power Current, I_{mp}	0.273 A
Short Circuit Current, I_{sc}	0.3 A
Cell Efficiency	16.0 %

The PV device is a 5-Watt GP005PA acquired from local electronics retailer Alexan. It is a polycrystalline module with 36 cells connected in series in a 2x18 layout. The module has a voltage temperature coefficient of 0.32%. Table 2 presents the parameters of the solar PV module used in this study according to the device's datasheet.

3.2. Technical Feasibility Tests through Simulation

Simulation of the TE system's generator performance was accomplished through applying the mathematical models in the matrix laboratory (MATLAB) software. The TE system was assumed to be installed to the backside of a PV module, where the latter acted as the former's heat source. Data gathered on PV performance—module temperature, irradiance, maximum power—together with corresponding meteorological data—average air temperature—available online (Weather Underground, 2014) as well as manufacturer data (Ferrotec Corporation, 2014) of the TE properties—module Seebeck coefficient, resistance, thermal conductivity—were utilized. Fig. 3 shows the general structure of how the software runs.

The same software technique was used to determine the total output power generated by a combined PV-TE system. This was compared with the output generated by a standalone PV system and analyzed.

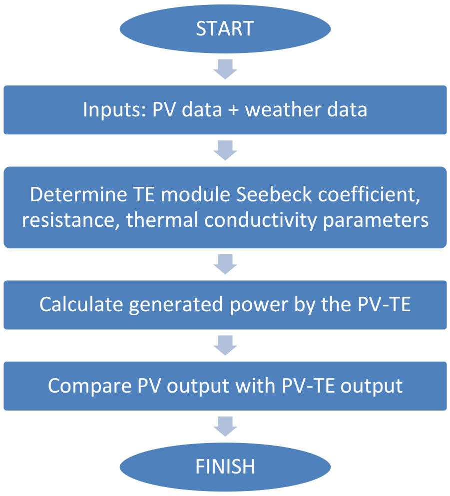

Fig. 3 Flow of the software program

Determining the thermal effect of the TE on the PV module was achieved through the relationship of the open circuit voltage (V_{OC}) of the PV with temperature. Among the attributes of the PV, the effect of temperature is most apparent to the V_{OC} (PV Education, 2015). A V_{OC} versus temperature profile of the GP005PA was used to model the thermal effects on the output of the PV:

$$V_{OC} = -0.0169T + 10.445 \quad \text{(Eq. 7)}$$

Data results from the combined performances of the two simulations of TE as generator to PV and TE as coolant to PV were collected and evaluated against a PV-only model. Using Eq. (4) the study was able to determine the total output power of the system which is analyzed against the characteristics of a PV-only system.

3.3. Hardware Implementation

A simple hardware implementation was designed to test the proposed PV-TE system. A total of eight modules of the TEC12706 were fitted on the backside of the GP005PA and were connected in series. They were attached and distributed evenly to the backside of the PV module. Each TE device had heat sinks attached to the side not in contact with the PV. Thermal paste was used to ensure thermal contact between the components. Additional metal reinforcement was added to secure the components in place and to act as an extra heat sink to dissipate the heat. LM35 probes were inserted to log temperature data for analysis.

The PV-TE system was first deployed in a controlled environment indoors to determine the best parameters for use in outdoor conditions. A 500-Watt Tungsten Halogen lamp was chosen as a light source because its spectra matches closely to that of the sun. Experiments were carried out under a 110 W/m^2 rating for irradiance with a 2-hour duration. The current-voltage (I-V) curve tracer developed by Peña et al. (2013) was used in this study for the characterization of the PV modules.

Outdoor deployment was carried out on a rooftop with the devices propped on a metal stand. The duration for each collection of data took around 6-7 hours from morning until late afternoon. Data for all circuits were logged using Arduino software which were later processed in MATLAB and Microsoft Excel.

4. Results and Discussion

4.1. Device Characterization

The eight TEC12706 TE devices used in the study were characterized individually then in series by means of applying electrical current to them in increments. Fig. 4 shows the corresponding graph for the characterization of the TE devices in series. It shows the linearity of V versus ΔT curve. Thus, ΔT increases as voltage increases.

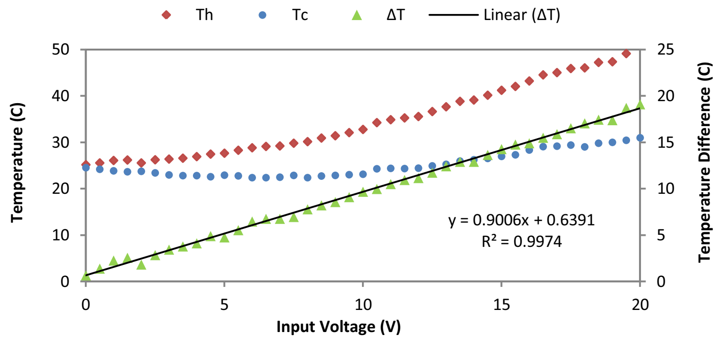

Fig. 4 **Characterization of the TEC12706 in a series of 8 modules**

The GP005PA PV device used in the study was characterized under outdoor conditions. The graphs in Fig. 5 exhibit the respective I-V and P-V curves with a solar irradiance of 919.8 W/m^2, temperature of 59.0 °C and a $P_{\max}$ of 5.802 W.

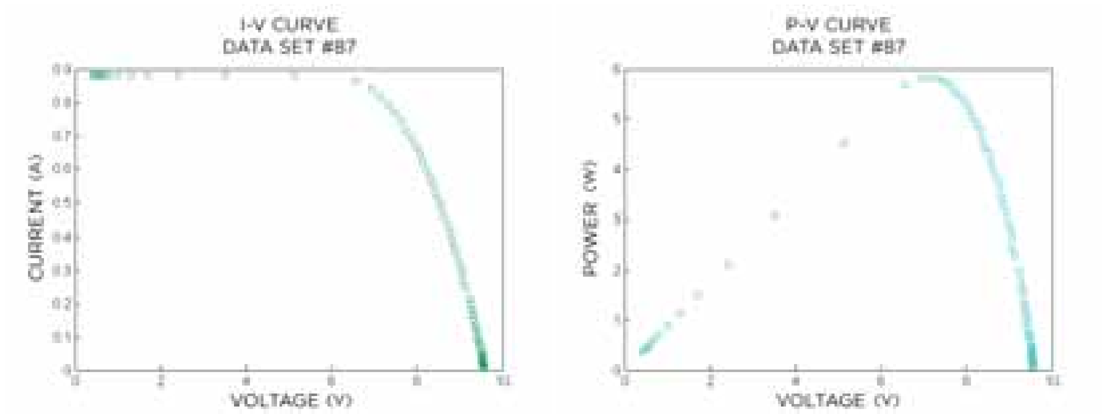

Fig. 5 **I-V and P-V Curves of the GP005PA with the sun as the light source**

4.2. Observations from Theoretical Modeling

One of the earlier TE models illustrated the attractive nature of the technology as a power generator in which a large output is possible given an equally large temperature gradient and with more modules used. For this model, the basis for maximum temperature is the highest estimated temperature for a solar PV module in conditions where irradiation is very high such as sometime around noon, which is 60 degrees Celsius. In ideal scenarios where the cooler side of the TE is dissipated well that it is at 0 °C, 60 °C in ΔT can be achieved. Fig. 6 shows the graphs of the TE output power versus temperature difference as a result of the simulation. In the figure, the maximum power (21 W) can be produced if 20 TE modules are placed at the backside of the solar PV module and $\Delta T = 60$ °C. Even with $\Delta T = 30$ °C, the TE can generate 5 W.

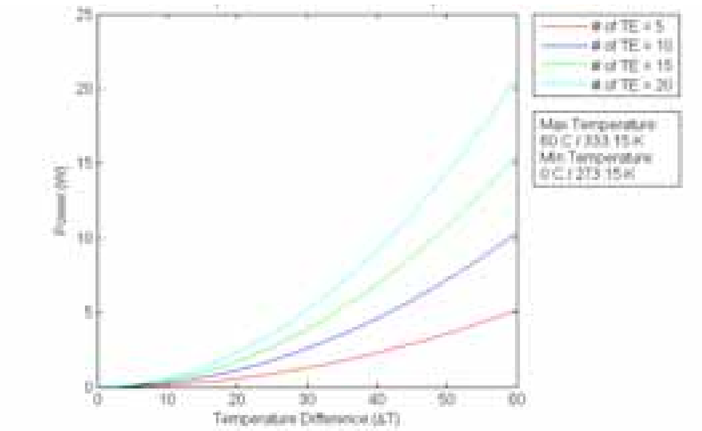

Fig. 6 **Graph for TE output power versus temperature difference**

The thermoelectric generation models used collected weather data (ie. irradiance, ambient air temperature) and PV data (ie. peak power, PV module temperature) from July 21, 2015, and TE attributes (ie. Seebeck coefficient, module resistance) to generate plots of TE and PV-TE system performances. Fig. 7 shows a comparison of the power output of the TE as a generator and the power output of the PV module, and the combined power output of the PV and TE. A comparison can be made of the power generated by the 5 W GP005PA PV device, an array of eight TEC12706 TE modules, and their combined output. It can be observed that solar irradiation and temperature have influence on the output power of the devices, while temperature levels appear proportional with the trend of the TE output. An average of 27.6% increase in PV output power was calculated when using the TE attachments compared to a PV-only setup.

The model to determine the thermal effect on the GP005PA PV device was designed using the parameters in Eqs. (6-7) and weather data from July 20, 2015. Variations in the temperature of solar PV modules greatly affect its open-circuit voltage V_{OC}. Thus, the V_{OC} parameter and its variations were investigated when the TE device was modeled as a coolant. Fig. 8 shows a comparison of the V_{OC} of the PV device with the TE device acting as a cooling mechanism, against the V_{OC} of the PV device alone. An average increase of 0.04% in the V_{OC} is noted.

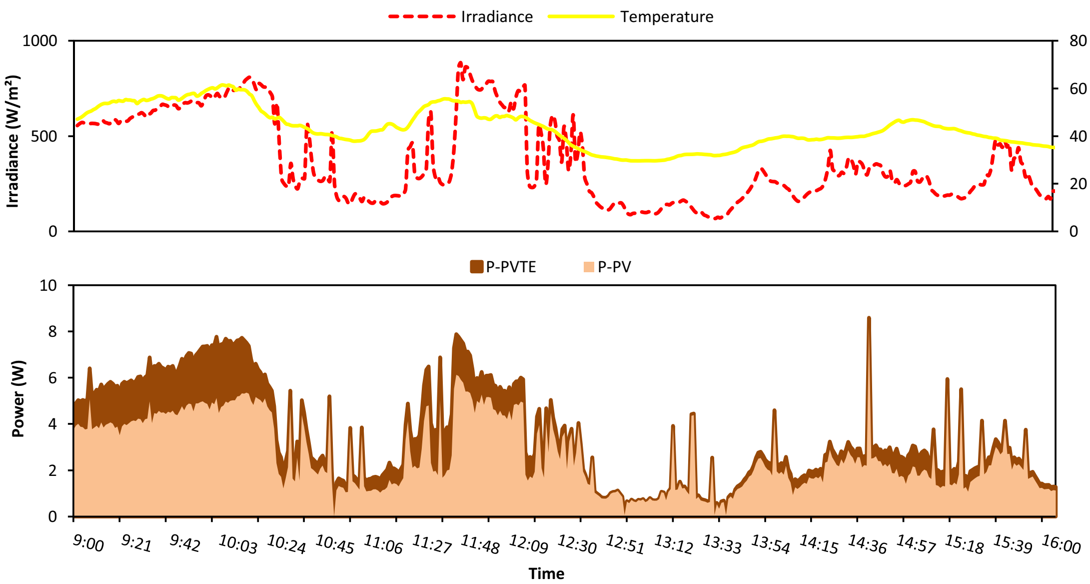

Fig. 7 **Comparison of the theoretical power output of the 5W Polycrystalline PV device (*P*-PV), and its combined output power with the TEC12706 TE device (*P*-PVTE) as a *generator***

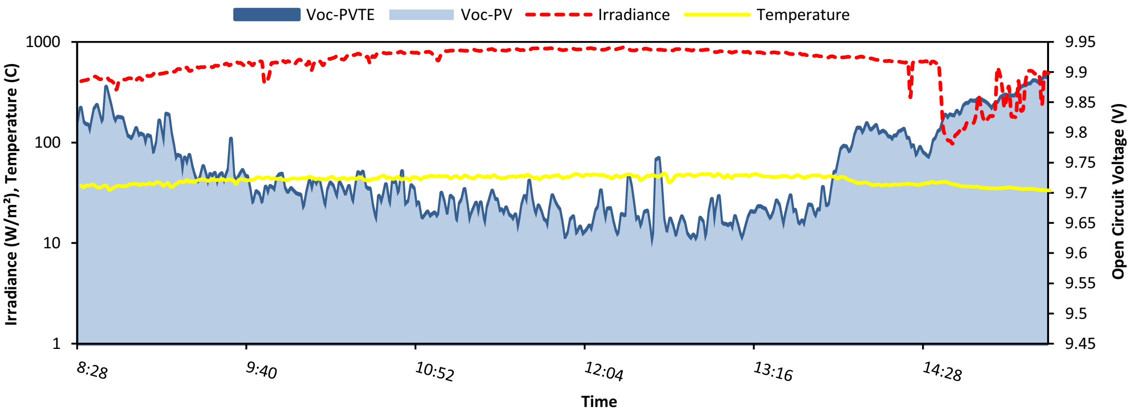

Fig. 8 **Comparison of the open circuit voltage output (V_{OC}-PV) of the 5W Polycrystalline PV device against the theoretical output V_{OC} of the PV with the TEC12706 TE device (V_{OC}-PVTE) as a *coolant***

4.3. TE as Generator

The results of the PV-TE prototype after it was deployed outdoors and observed for a number of days revealed a small but noticeable improvement compared to the standalone PV. Fig. 9 shows a comparison of the output power of the PV-TE system against the output power of the stand alone 5W PV module during outdoor deployment. An average increase of 1% in output power for the combined PV-TE was noted. Measurements were obtained on another day and an average increase of 1.9% in output power was observed. These however are not enough to match the projected increase in output power by the PV-TE model which theoretically indicated a 27.6% increase. It can be noted that similar to the model, the actual results showed that the trend of the output power followed irradiance levels, thus the current generated by the solar PV module dominated over the temperature variations and the effects on V_{OC}. The graph also revealed that the most noticeable improvement was in the morning when irradiance levels were observed to be high. This translates to high module temperature but lower ambient temperature, hence, greater ΔT.

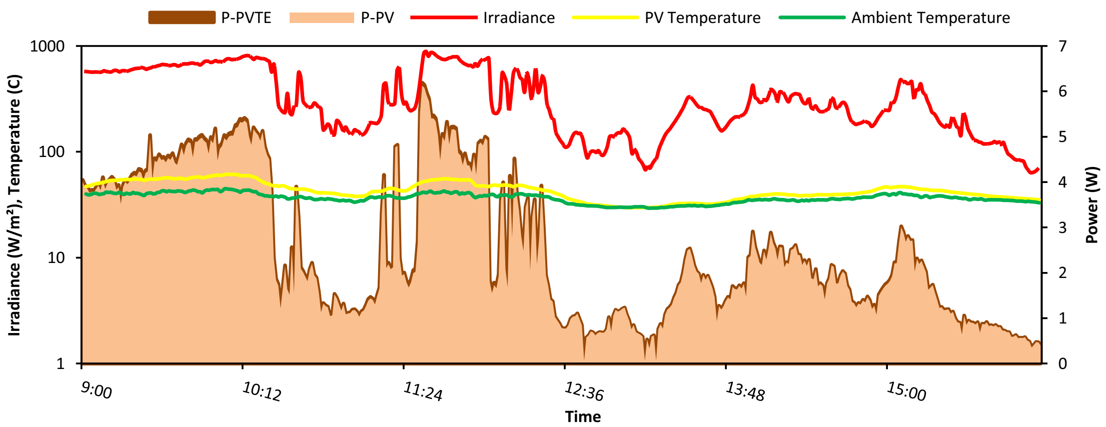

Fig. 9 **Comparison of the experimental output power of the PV-TE system (*P*-PVTE) with the TE as *generator* against the output power of the 5W PV alone (*P*-PV) after outdoor deployment**

4.4. TE as Coolant

Fig. 10 shows a general overview of the GP005PA PV device with TE attachments acting as a cooling mechanism to it. The 8V that was supplied to the TE array causing the cooling effect was determined in earlier lab tests where it showed the most promising results. It would seem that there is not much effect, in fact experimental results were less by an average of 3.7% from the simulated results. One noticeable observation is the ΔT indicative of cooling effectiveness when the difference is greater, which is apparent during the morning and late afternoon of the day. A zero to negative ΔT at midday around noon when PV temperature is hotter than the ambient, implies that the TE is not ideal as a coolant during this time.

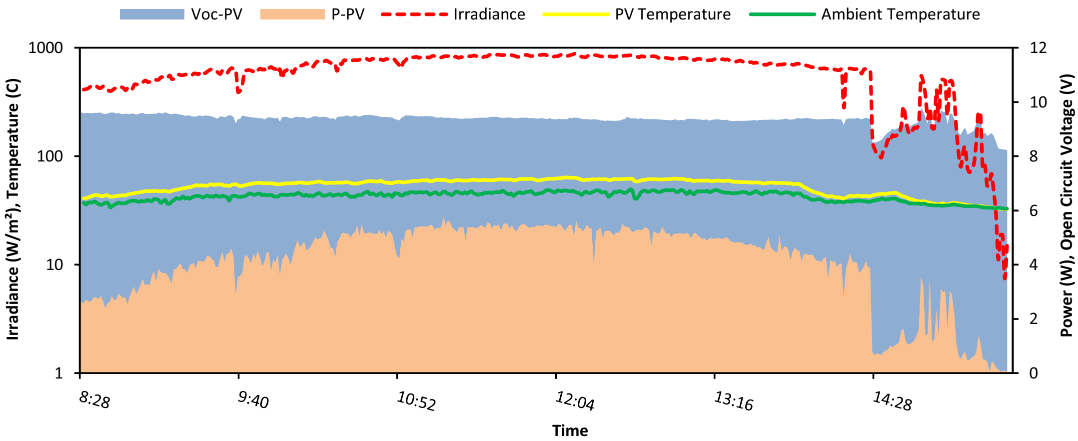

Fig. 10 **Experimental effect of the TEC12706 TE devices as a *coolant* to the 5W PV device on its V_{OC} and P_{max} after outdoor deployment**

The study also considered the relationship of irradiance to the performance parameters of the PV-TE and standalone PV systems by plotting irradiance versus output power for TE as generator (TEG) and irradiance versus V_{OC} for TE as coolant (TEC) from the data obtained in this study, which are shown in Fig. 11. Fig. 11a shows that the TEG has little effect on the power output though a small improvement in output power of the PV-TE system is observed. Fig. 11b shows that there is an improvement for PV performance with the TEC attachments. In general, at lower irradiance levels, the V_{OC} output of the PV-TE system is higher compared to a PV-only setup. This would indicate that at this range up to 600 W/m^2, it is when the TE cools the PV most effectively. This is supported by the Irradiance versus ΔT plot in Fig. 12 which shows that ΔT is negative (ie. hot side is cooler than the side emitting the cooling effect therefore ineffective) at high irradiance levels. Therefore, the TE devices are not recommended in cooling at high irradiance levels. On the average the difference is about 2% in V_{OC} in favour of the PV with TEC. Efficiency for this system taking into account the input needed by the TE calculated against the output of the PV is at 11.4%.

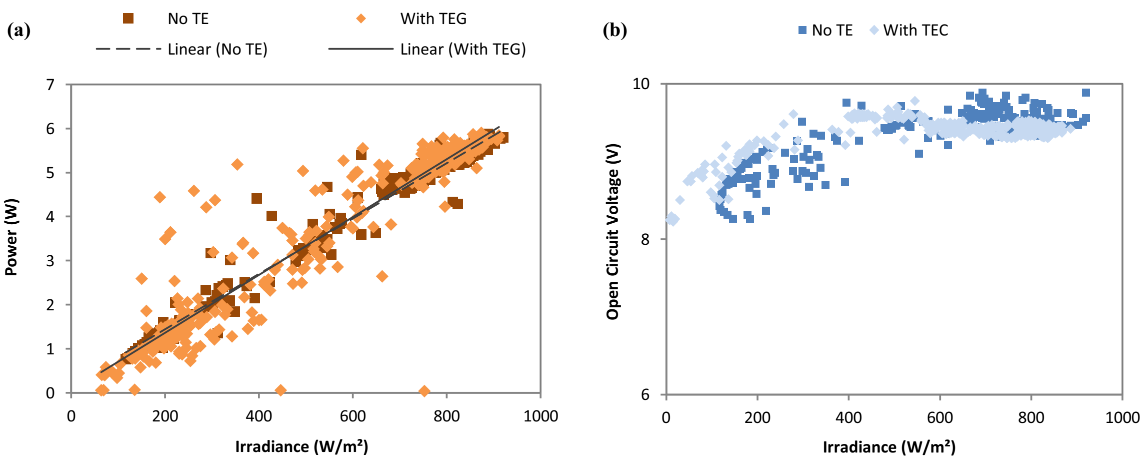

Fig. 11 **Results of the performance parameters for PV-TE and PV-only measured against Irradiance: (a) output power for PV-TEG (as *generator*), and (b) open circuit voltage for PV-TEC (as *coolant*)**

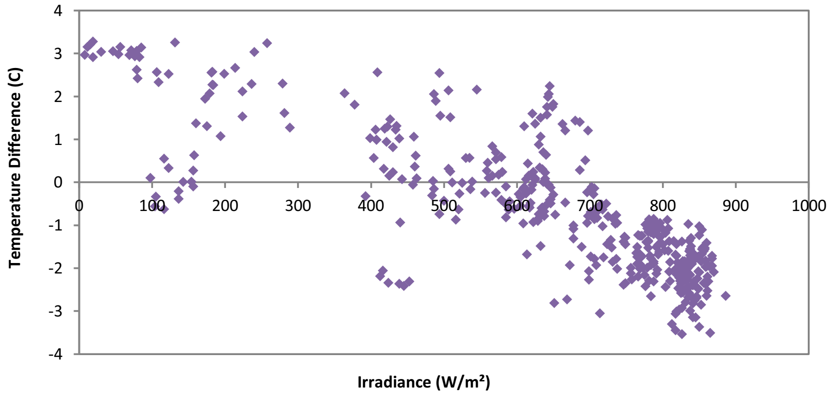

Fig. 12 **Irradiance versus Δ*T* of the TEC in a PV-TE system**

5. Conclusion

This study has shown that thermoelectric application has an effect on PV performance. In theory, the power generated by a PV-TE system with the TE in generator mode has a 27.6% improvement when compared to a standalone PV-only setup. Moreover, a 0.04% increase in the V_{OC} of the PV is also predicted when the TE acted as a cooling mechanism. After outdoor deployments were carried out to put the theory to the test, the increase in output power recorded for the PV-TE system with TEG was only about 1−1.9%. There was a noticeable improvement however on the TEC influence on the V_{OC} of the PV when it produced a 2% increase as compared to the standalone PV based on aggregated data. These results may be small but notable enough to indicate that the TE indeed does improve the power output of the solar PV module. Future research is strongly recommended with added features to the TE system such as better heat sink design and the utilization of boost converters that can potentially augment the effects of the TE on the PV module.

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