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Performance Analysis of Solar Photovoltaic (PV)-Thermoelectric (TEG) Hybrid Energy System for Electricity Generation

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Abstract

Original Research Article

The solar spectrum responsible for PV operation comprises the ultra-violent, visible and invisible radiation. The increase in cell temperature due to the invisible radiation in the solar spectrum reduces the solar PV performance. This research investigated the performance of solar PV-TEG hybrid energy system for energy optimization in comparison with simple solar PV system. The solar PV-TEG hybrid energy system is one on which thermoelectric generators (TEG) were couple with PV module for conversion of the excess heat energy due to rise in cell temperature to electrical energy. The output parameters of both systems such as; short circuit currents open circuit voltages and PV cell temperature were measured with respect to incident solar radiation. The power production and efficiencies for the simple PV and hybrid PV-TEG systems were evaluated and compared, The results revealed that at maximum value of 920 W/m^2 average hourly sun radiations, 57.9 W useful PV power input was simultaneously utilized by the simple PV and hybrid PV-TEG systems. The operating temperatures of the simple PV and the hybrid PV-TEG systems varies from 64.5°C to 58.9°C which is 9.94%, reduction. The simple PV and hybrid PV-TEG short circuit currents and open circuit voltages varies with values (17.8 to 20.13 V) and (0.56 to 0.57 A), which have increased by 1.78% and 14.1% respectively. However, with respective values 10.14 W and 11.58 W of power outputs an increase of 14.5 % was realized. These enable enhancing respective 17.5 % and 20 % energy efficiencies. The overall power output and efficiency of the hybrid PV-TEG energy system reported were 11.67 W and 20.2% which showed increased by 15.09 % and 15.43% respectively compared to the simple PV system. Moreover, the statistical analysis conducted reported quality of the measured results and inequality of the respective pairs of output values with P-values of 0.000 in each case. Therefore, integrating PV module with TEG enables reduction of cell temperature and optimizes the PV power output and efficiency of the solar PV system.

Keywords: Solar Radiation, Photovoltaic, Thermoelectric, Temperature, Hybrid system.

1.1 INTRODUCTION

Electrical energy is essentially needed for socio-economic development of every nation. The Population growth and industrialization have been reported to contribute to the unprecedented increase in energy demand. It has been estimated that, by 2040 the global population will attain 9.2 billion people out of which 860 million will have lack access to electricity (International Energy Agency, 2019). It has also been expected that the global energy demand will rise by 20% from 2017 to 2040, while global electricity demand will rise by 60%. This shows that the electricity generations need to be increase in order to meet up with frequent rise in demand.

Solar energy resources as an alternative, clean abundantly available almost everywhere and could be harnessed for electricity generation through solar thermal and photovoltaic systems. Solar photovoltaic is a system in which solar modules or cells capture energy photon from solar radiation to generate electricity, it is a prominent technology and it is developing so rapidly. In addition to that, PV module efficiency is affected by the operational temperature due to the direct conversion of solar energy into heat that takes place in the module. The decrease in PV temperature improves the power output

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thereby, enhancing better efficiency. The heat energy which is otherwise wasted into the environment could be utilized to generate electricity by using Thermoelectric Generators (TEG). Asides the photovoltaic which generates electricity directly from sunlight, the thermoelectric generator (TEG) can also generate electricity directly from thermal energy. A thermoelectric (TE) module is a bi-directional energy converter which can be used for generating electricity or for heating/cooling. When it is used for electricity generation, it is referred to as a thermoelectric generator, while it is called a thermoelectric cooler (TEC) when used for cooling/heating. A combination of a PV and a TEG could potentially have a higher efficiency, i.e. be able to convert a larger fraction of the incoming solar radiation into electricity, than a PV alone.

Although photovoltaic systems have been commercially available for several years, but elevated temperature in the PV, limited conversion efficiency and dust accumulation offered barriers to their widespread application (Makki *et al.,* 2015). Operational temperature has tremendous effect on PV performance. Efficiency of the PV module has been reported to decreases by a range of 0.25% to 0.5% per degree Celsius depending on the cell material used in the PV fabrication (Grubisići *et al.*, 2016). This means that even the slight decrease in PV temperature can significantly increase its efficiency therefore, cooling techniques are very essential to PV systems. Therefore, in order to reduce the cell temperature, the technology of hybridizing PV with thermoelectric modules would be employed. This would systematically cool the PV module; slightly decrease the PV cell temperature and significantly increases the system efficiency. In this cooling process, the excess heat which is otherwise wasted would be converted by the thermoelectric generator into electricity accounting to further increase in system power output and efficiency.

Consequently, researchers have focused on a complementary technology called photovoltaic-thermoelectric generator (PV-TEG) which could make use of the advantages of both individual technologies. Furthermore, photovoltaic cells utilize the visible and ultraviolet regions of the solar spectrum while the thermoelectric utilizes the infrared region of the solar spectrum. Therefore, combining both technologies would allow a wider utilization of the solar spectrum for energy harvesting. In addition, the synergetic integration of the photovoltaic and thermoelectric generator could result in an improved photovoltaic efficiency, and an increase in electricity generation per unit area compared to the conventional PV only.

The aim of this research is to conduct comparative analysis of solar hybrid photovoltaic-thermoelectric generator for electricity generation. These were achieved by installation of simple PV and hybrid PV-thermoelectric systems and experimental study their performances under climatic condition of Aliero, analyzing the output parameters observed from simple PV and hybrid PV-thermoelectric systems and conducting comparative analysis between the simple PV and hybrid PV systems results.

1.2 Photovoltaic System

The photovoltaic effect is the generation of electrical voltage across a material when it is exposed to light. A photovoltaic cell is a junction between two semiconductors, p-type and n-type, when photons strike on the junction; electron-hole pairs are generated. The induced electric field diffuses and separates these electron-hole pairs at the junction; these separated charges travel in opposite directions, eventually flowing in the external circuit, hence producing electrical current as shown in Figure 1.1.

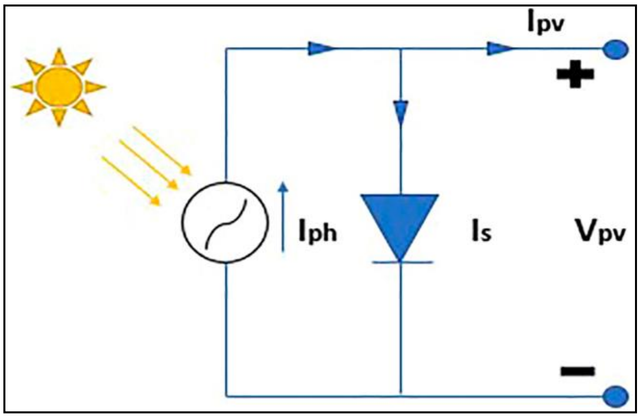

Figure 1.1: Simplified equivalent circuit of PV cell (Huen and Daoud, 2017)

The power input to the solar PV module can be express as the product of incoming radiation on to PV module (W/m^2) and the exposed surface area (m^2). The PV module input power can be estimated by using equation 1.1 as:

$$P_{in} = GA_{pv} \quad (1.1)$$

Where p_{in} is the power input, G is the solar irradiance, and A_{pv} is the exposed surface area of the PV module.

The maximum power output generated by the PV module is express as the product of maximum current and maximum voltage generated by the PV module. The equation 1.2 determines the maximum power output of a module.

$$P_{mp} = I_{mp} * V_{mp} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.2)$$

The Fill Factor of the solar PV module can be obtained from the short circuit current I_{sc} and open circuit voltage V_{oc} from equation 1.3.

$$FF = \frac{V_{mp}*I_{mp}}{V_{oc}*I_{sc}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.3)$$

The efficiency of the PV module can be expressed by inputting power input and output of the PV module in equation 1.4 as;

$$\eta_{pv} = \frac{FF*V_{oc}*I_{sc}}{P_{in}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.4)$$

1.3 Thermoelectric System

Thermoelectricity (TE) is essentially a bidirectional energy transformation technology for the conversion of thermal energy into electricity, and vice versa. This technique offers an alternative to conventional processes used for heating, cooling, and power generation from waste heat. The primary benefits of adopting these thermoelectric (TE) devices include gas-free emission, noiseless operation, significant scalability, vibration and maintenance-free operation without moving components, and long-term operational reliability (Muhammad *et al.*, 2021). Thermoelectricity is the electricity produced from heat and it categorizes into two-way process, which is known as the Seebeck effect and Peltier effect. Others are Thomson and Joule effects.

1.4 Solar Energy Spectrum

The combination of photovoltaic and thermoelectric allows for the wider use of the solar spectrum. This is because PV converts the ultraviolet and visible regions (200 – 800nm) of the solar spectrum into electricity while TEG converts the infrared region (800-3000nm) into electricity (Tritt *et al.*, 2008). Solar PV module utilizes visible range of solar radiation only, but the infrared range is transmitted and induces thermalization of PV cells which adversely affects its efficiency and output power (Dimri *et al.*, 2017). The panel rise in temperature does not only decrease the efficiency but also reduces the life span of the panel. However, in the solar spectrum shown in Figure 1.2, it had also been observed that 58% which is a component of Ultra Violent and visible light is converted in to electricity by the PV module. While the remaining 42% which contains only invisible radiation is converted into heat energy and utilizes by the thermoelectric generator for electricity generation.

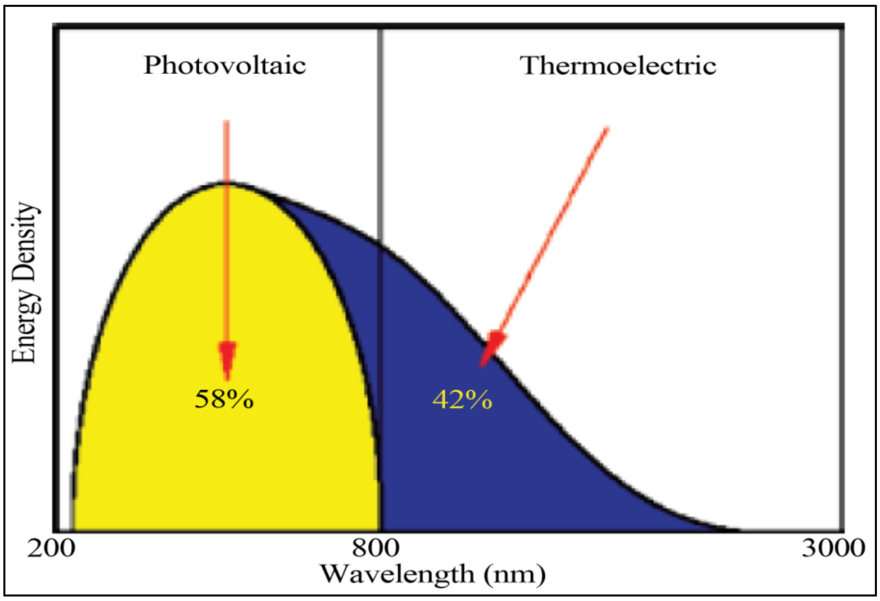

Figure 1.2: Sun radiates energy as a 6000 K blackbody radiator with part of the energy in the ultraviolet (UV) spectrum and part in the infrared (IR) spectrum (Jarman *et al.*, 2013)

1.5 Hybrid Photovoltaic-Thermoelectric Systems

The direct coupling method involved coupling of TEG module on the rear side of the PV module. Combining a photovoltaic module and a solar thermoelectric generator would enable photons outside the range of a particular solar cell's narrow absorption wavelength to be directed to the TE modules which generates electricity by the thermoelectric effect. Doing this would allow energy conversion efficiency to be increased while simultaneously reducing the heat dissipated by the PV module. Figure 1.3 present a schematic direct coupled PV-TEG hybrid system (Muhammad *et al.*, 2021).

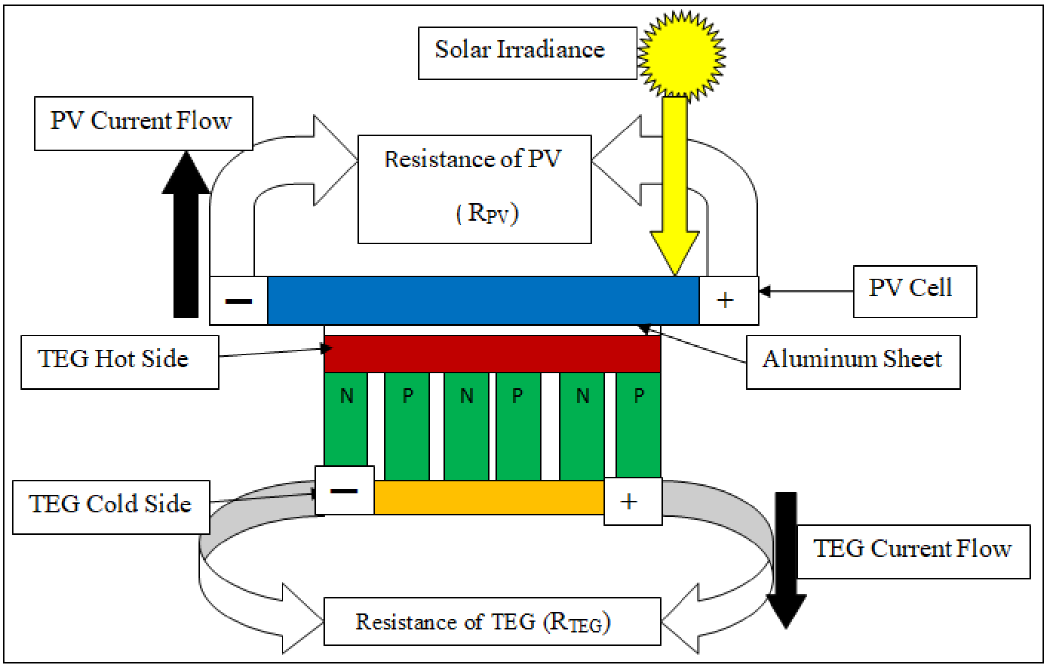

Figure 1.3: Schematic diagram of a PV-TEG hybrid system

The overall conversion efficiency of the hybrid PV-TEG system can be expressed as the sum of the individual efficiencies of PV (η_{pv}) and TEG (η_{TEG}) in equation 1.5 (Narducci *et al.*, 2018)

$$\eta_{PV/TEG} = \eta_{PV} + \eta_{TEG} = \frac{P_{PV}}{P_{in}A_{PV}} + \frac{P_{TEG}}{P_{in}A_{PV}} \quad \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots (1.5)$$

Where P_{PV} is the output power of the PV module, P_{TEG} is the TEG output power, A_{PV} is the surface area of the module, calculated by multiplying the length with the width of the PV module, and P_{in} is the input solar power.

Integrating thermoelectric devices into photovoltaic systems can enable the efficient thermal management of PV thus, enhancing its overall performance. When thermoelectric generators are combined with PV, depending on the integration method of the PV-TEG, the TEG can utilize the waste heat from the PV to generate some electrical energy if it is properly cooled and there is sufficient temperature difference across it. In addition, the overall hybrid system performance could potentially be enhanced by the integration of thermoelectric generators into PV if the system is properly designed although there is a possibility of reduced performance due to the complex relationship between PV and TEG. In a combined system, the TEG is mounted directly on the back of the PV (Huen and Daoud, 2017).

The technology for conversion of heat into electricity through thermoelectric generators is prominent. This is because a lot of domestic and industrial heats which are usually wasted into the environment are being converted into useful energy. The numerous media through which thermoelectric generators could harnessed excess heat into electricity involved; domestic and industrial heating systems, solar concentric devices and flat plates and photovoltaic systems. Many researches based on these energy conversion principles were conducted towards improving the PV energy efficiency due to the under developing technology. The combination of PV panel with TEG module can exhaustively absorb a wide range of solar radiation spectrum either in form of infrared energy or ultraviolet energy. Therefore, the concept of photovoltaic thermoelectric hybrid system is feasible since the method of combining PV with TEG can fully utilize the solar spectrum in theory. This is the greatest advantage of the hybrid system over single PV and TEG system operation respectively (Guiqiang *et al*., 2018).

Kraemer *et al.*, (2008) presented a general optimization methodology for a hybrid PV-TEG system using the spectrum splitting method. Three different PV types were studied experimentally, and it was found that the amorphous silicon cell provided the best hybrid system efficiency of 13.26% when a TEG with efficiency of 8% was used. A comprehensive study of a spectrum splitting concentrated PV-TEG system was performed (Ju *et al.*, 2012). The influence of cut-off wavelength, concentration ratio and heat transfer coefficient on the performance of the hybrid system were studied and optimization of the hybrid system was performed. They found that the TEG contributed about 10% of the total hybrid system power and the optimized hybrid system efficiency was about 27.49%. A comparison of the hybrid system with the conventional PV system was made and it was found that the hybrid system is better suited for high concentration conditions due to its enhanced performance. Furthermore, the optimum design for a concentrated spectrum splitting PV TEG was proposed by *Yin et al.*, (2018) to optimize the distribution of solar energy in a spectrum splitting CPV-TEG without compromising the optimum design state of the individual systems.

Yang *et al.*, (2018) studied the performance of a spectrum splitting PV-TEG system using numerical simulation. It was found that the efficiency of the hybrid system increased by 2.67% and 2.19% compared to that of the PV only system at concentration factors of 30 and 100 respectively. Bjørk *et al.*, (2018) studied the maximum theoretical performance of a PV-TEG system without concentration. The authors used an analytical model to study the performance of the system and found that the hybrid system using spectrum splitting could achieve a maximum efficiency increase of 1.8 percentage point compared to the PV only system.

Furthermore, Liang *et al.*, (2018) performed an experimental and numerical investigation on the performance of a spectrum splitting concentrated hybrid PV-TEG system. Results showed that the direct normal irradiation (DNI), optical concentration ratio and height ratio of the two TEG stages could significantly affect the performance of the hybrid PV-TEG system.

Muhammad *et al.*, (2021) works on experimental model of a hybrid photovoltaic-thermoelectric generation (PV-TEG) system using ten bismuth telluride-based thermoelectric modules and 10 W polycrystalline silicon-based photovoltaic modules in order to recover and transform waste thermal energy to usable electrical energy, ultimately cooling the PV cells. Their result shows that the operating temperature of the PV module in the hybrid system is reduced by 5.5%, from 55°C to 52°C. However, they observed that due to a drop in temperature and the addition of some recovered energy by thermoelectric modules, the total output power and conversion efficiency of the system have increased. They concluded that the hybrid system’s cumulative output power increased by 19% from 8.78 to 10.84 W, compared to the simple PV system. Also, the efficiency of the hybrid PVTEG system increased from 11.6 to 14%, which is an increase of 17% overall.

2.1 MATERIAL AND METHODS

2.1 System Components Choice

The basic components for solar PV-TEG hybrid system consist of a solar PV module, thermoelectric generator and heat sinks. Large number of manufacturers of PV modules and TEG modules available in the World prescribed the cost and specifications of their products based on the materials used and the technology employed. The solar PV module used in this research was selected base on the availability, cheapness, temperature coefficient of performance and efficiency. Two pieces of polycrystalline silicon based PV module, Bona AP-PM-10 model was used in this research (see Figure 2.1 and Table 2.1 for PV module and its specification). However, for the purpose of lowering the cell temperature and improving the power output and efficiency at the same time six (6) thermoelectric generators were glued at the rear base of one PV module. The thermoelectric generator module was choosing base on availability, cheapness and low operational temperature. Six pieces of Bismuth telluride (Bi_2Te_3) thermoelectric modules were used in this study because they are the most commercially available on the market. Meanwhile, the heat sinks were choose base on higher thermal conductivity, availability and cheapness of the products.

Table 2.1: Specification of Solar PV module

Parameter	**Specification**
Maximum Power (P_{max})	10 W
Open circuit Voltage (V_{oc})	21.6 V
Short Circuit Current (I_{sc})	0.62 A
Voltage (V_{max}) at Maximum Power (P_{max})	17.5 V
Current (I_{max}) at maximum Power	0.58 A
Output Tolerance	± 5 %
Dimension	35 cm x 24 cm x 15cm

Table 2.2: Specification TEG module

Parameter	**Specification**
Model	SP 1848-27145
Materials	Bi_2Te_3
No. of thermocouples	127
Dimensions	40 mm x 40 mm x3.4 mm
Current at 100 ^oC	0.669A
Open circuit Voltage	4.8 V
Operating Temperature	150 ^oC
Weight	30 g

Figure 2.1: Simple PV and Hybrid PV-TEG

2.2 Experimental setup

The experimental setup consists of Solar Photovoltaic Module (SP) without thermoelectric modules and Hybrid Solar Photovoltaic-Thermoelectric (HSPT). The HSPT was made by mounting the hot sides of the thermoelectric modules on the rear side of the of the PV module with glue in series arrangements. However, the heat sinks were glued on the cooled side of the thermoelectric generator and the outputs of the thermoelectric modules were connected to the solar Photovoltaic module terminals at appropriate polarity. Two polycrystalline photovoltaic panels of 10 W were used to carry out the comparative performance analysis as shown in Figure 2.1. PV modules were positioned at a fixed tilt angle of 13° towards the south. To evaluate the performance of a simple PV and hybrid PV-TEG system, the setup was tested under the climate conditions of Aliero (12.288° N, 4.4735° E), Nigeria. The experiments were carried out from 8 am to 6 pm in ten (10) consecutive days of winter from 22nd February to 4th March, 2024.

Figure 2.2: Block Diagram of the experimental setup

The practical experimental setup made for data collection is shown in Figure 2.2. The sun radiation at the vicinity of the experimental set up, the ambient temperature, the PV operational temperature, the open circuit voltages and short circuit currents of the PV module and thermoelectric PV hybrid were measured for ten days in each case and average hourly results were computed.

2.3 Data and performance Evaluation

The sun radiation and ambient temperature and wind speed at the vicinity of the installed system were measured by using Digital Phyranometer and Digital Anemometer respectively. The temperature of the rear surfaces of the PV module and Hybrid PV-TEG and temperature of the cold side of the TEG were measured by using Digital Multi –channel thermometer. The short circuit currents and open circuit voltages from the PV module and Hybrid PV-TEG were measured by using Digital Millimeters. The data were collected at the interval of 20 minutes from 8:00 am to 6:00 pm for ten days and average hourly results were evaluated. The average hourly data being recorded for solar irradiance, ambient temperature, operation temperatures and that of the respective short circuit currents and open circuit voltages were used in equations for estimation of system performance parameters. The average power input was estimated by using the average hourly sun radiation data and the dimension of the modules (0.063 m^2). The average hourly temperature difference between the hot and cold sides from the hybrid PV-TEG were obtained. The average hourly power outputs from the simple PV and hybrid PV-TEG were estimated by multiplying the average hourly short circuit currents and open circuit voltages. The average hourly efficiencies for the respective simple PV and hybrid PV -TEG were computed by using the average power inputs and outputs in equations (1.3 and 1.4). The overall efficiency of the PV-TEG hybrid systems were computed by using equation (1.5) and the results were analyzed.

Furthermore, comparative statistical analysis between the mean difference, mean deviation and mean error from simple PV and hybrid PV output parameters was conducted by using Minitab 2018 software. The confidence hypothesis tested under t-t paired test was to find out whether the two results are consistent with each other. The null hypothesis was between H_o, $\mu_d = \mu_o$ and H_1, $\mu_d \neq \mu_o$ at 95% confidence interval, zero (0) test mean and not equal alternative has been chosen. The statistical differences between, pairs of currents, voltages, power outputs and cell temperatures and efficiencies were tested using the same prescribed method of paired t- test. The mean deviations, mean differences and mean errors of the parameters were determined. The values of T-values and P-values were used for testifying the consistency or inconsistency of the paired data.

3.1 RESULT AND DISCUSSIONS

3.2 Results of Solar Irradiance and Useful Power input

Results from Figure 3.1 and 3.2 presented the horizontal solar radiation that stroked the surface of the solar module and the useful input power utilized in specific area of solar module. It had been noted a complete dependency of the useful power input on solar radiation provided the area of the solar module is the same. Considering Figure 3.3, the relationship between the average hourly solar radiation and useful power input was highlighted. The maximum useful power input value of 57.9 W observed by 1:00 pm, meant that, the PV module absorbed 920 W/m^2 solar radiations on its 0.063 m^2 area. Moreover, by taking the components of solar spectrum that only 58 %, that consist of the ultraviolent and visible radiation is responsible for electricity production by PV module. This meant that only 58 % of 57.9 W which is thirty three 33.6 W was utilized by the PV module for the generation of electricity. Additionally, the lower values of useful power inputs been observed during morning and evening periods were due to the respective lower sun radiations during these periods.

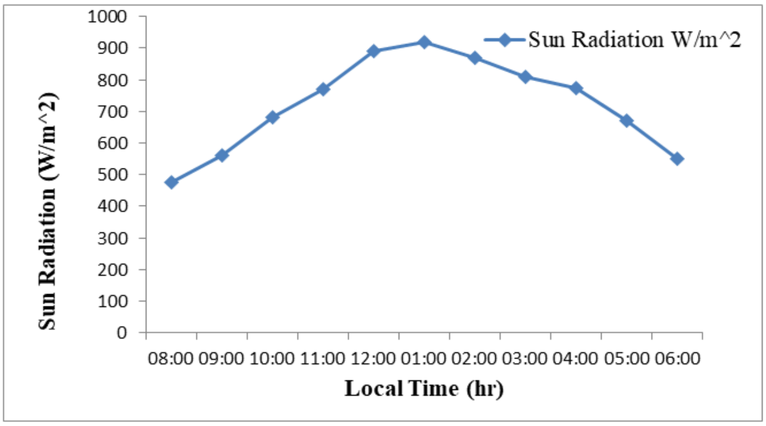

Figure 3.1: Graph of sun radiation verses Local Time

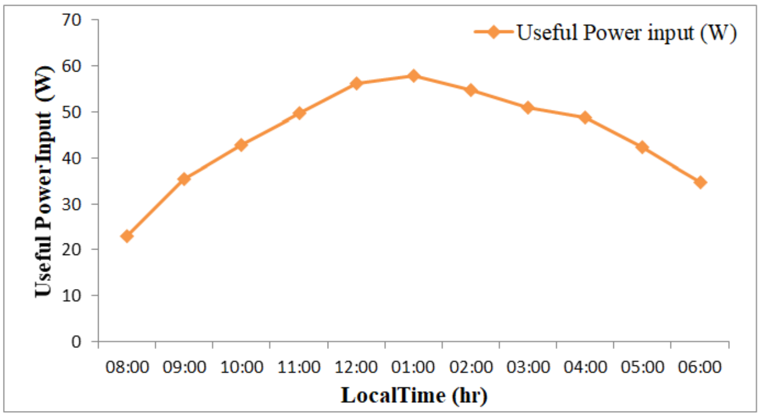

Figure 3.2: Graph of Useful Power input Verses Local Time

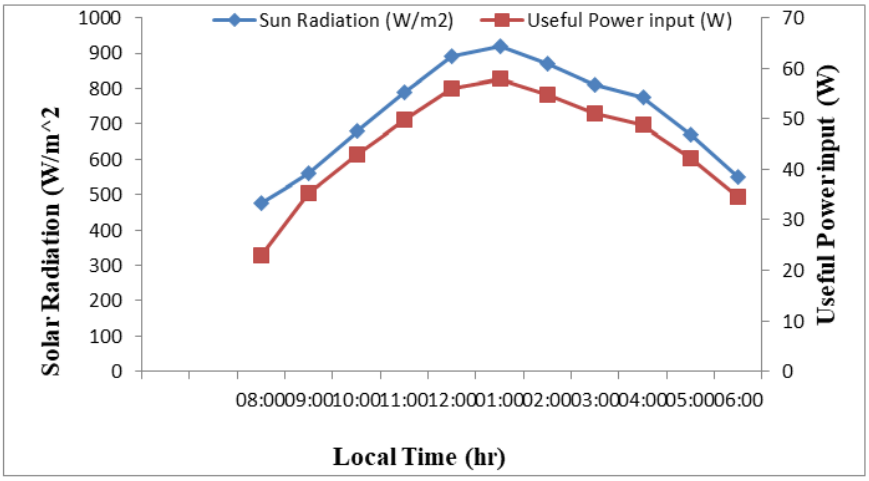

Figure 3.3: Graph of Relationship between Solar radiation and Useful Power input

3.3: Result of Transient Temperature

The transient temperature difference between the simple PV and hybrid PV–TEG systems has been observed in Figure 3.4. These temperatures depend on solar radiation and its increased on top simple PV module at every instant was due to the absorption of invisible component in solar radiation. As solar irradiance increases by intensity, the useful power input rises, which directly utilizes by the PV module to generate heat energy. But it rather decreased on the rear part of the hybrid PV-TEG system due to action of thermoelectric generator and heat sinks. It has been noted that at maximum solar irradiance of 920 W/m^2, PV modules received 57.9 W on its 0.063 m^2 to rise the PV cell temperature to the higher value of temperature variation been realized by 1:00 pm range from 65.4^{o}C to 58.9^{o}C is meaning that the temperature on the top of the simple PV was 65.4^{o}C and that on the heat sinks of the rear part of the hybrid PV-TEG was 58.9^{o}C. This leads to temperature transient by 6.5^{o}C which is 9.94% reduction. However, this temperature was used by the thermoelectric generator to generate additional electrical power.

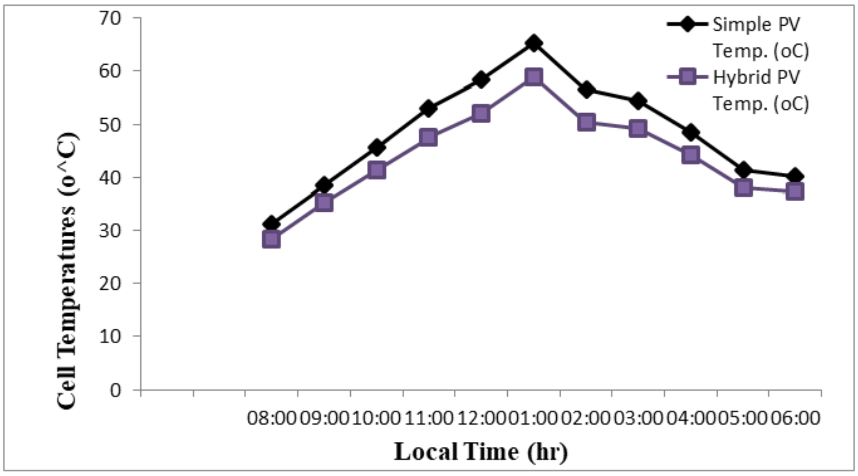

Figure 3.4: Graph of Transient Temperatures for simple PV and hybrid PV-TEG System

3.4: Result of Transient Current and Voltage Outputs

The result from Figure 3.5 presented transient short circuit current outputs and their relationship due to simple PV and hybrid PV-TEG systems. The average hourly transient short circuit currents from both simple PV and hybrid PV-TEG have increased at every instant. The increased showed at 1:00 pm by 1.78 % meant that, the current flows was due to the action of ultraviolent and visible rays in the incident solar radiation on the PV module. Consequently, out of 57.9 W of solar useful power input, only 33.58 W which is 58% was converted to electrical current by the PV module. Meanwhile, the result for open circuit voltages been presented in Figure 3.6 showed a potential difference of 17.8 V and 20.31 V at 1:00 pm from simple PV and hybrid PV-TEG respectively which is 14.1% increased. This increase in open circuit voltage was due to the action of thermoelectric generator which causes a decrease in cell temperature, thereby increases the potential difference.

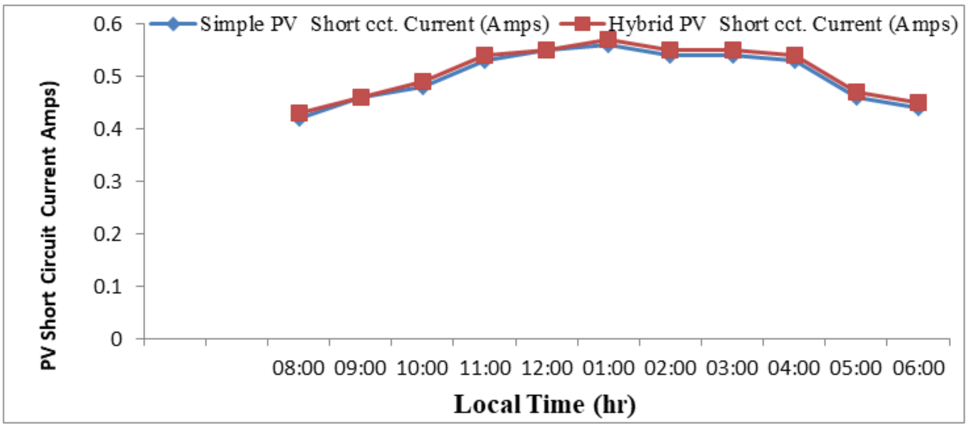

Figure 3.5: Graph of Short Circuit Currents for Simple PV and Hybrid PV-TEG system

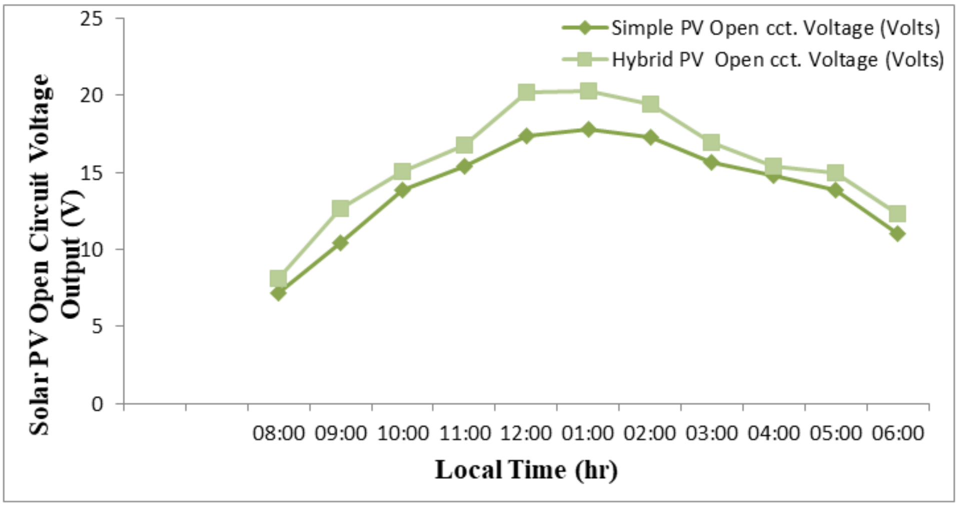

Figure 3.6: Graph of open Circuit Voltage for Simple PV and Hybrid PV-TEG Systems

3.5 Result of PV Power Outputs

The maximum average hourly power outputs generated from simple PV and hybrid PV-TEG systems at 1:00 pm were reported in Figure 3.7 with values 10.14 W and 11.58 W respectively. This meant that, due to the increased in short circuit current and open circuit voltages during this period by 1.78% and 14.1% respectively, the power output has increased by 11.64%.

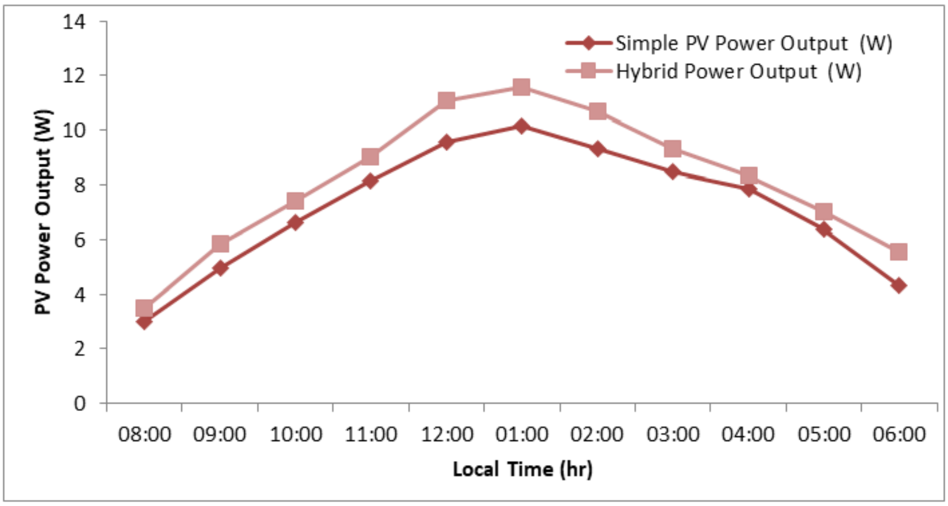

Figure 3.7: Graph of Power outputs from Simple PV and Hybrid PV-TEG System

3.6: Result of Effects of Temperature on Power Output and TEG and efficiencies

Furthermore, from Figure 3.8, the result presented for relationship between the power outputs and reduction in temperature, highlighted an increased of power output from the hybrid system by 11.46% due to 6.5 ^{0}C which is 9.94% temperature reduction compared to simple PV system. The result for relationship between the efficiencies of simple PV and hybrid PV-TEG systems been presented in Figure 3.9. This showed efficiencies increased in the morning, afternoon and evening increased of 2.1%, 2.5% and 2.0% respectively by the hybrid PV-TEG compared to simple PV systems.

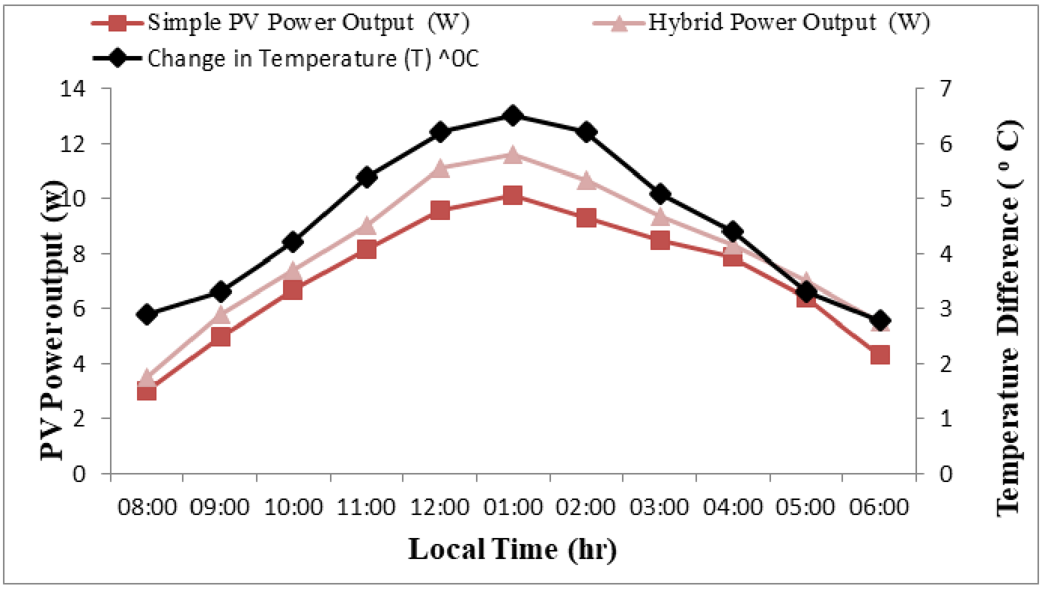

Figure 4.8: Graph of Effect of Cell Temperature Reduction on Simple PV and Hybrid PV-TEG System Outputs

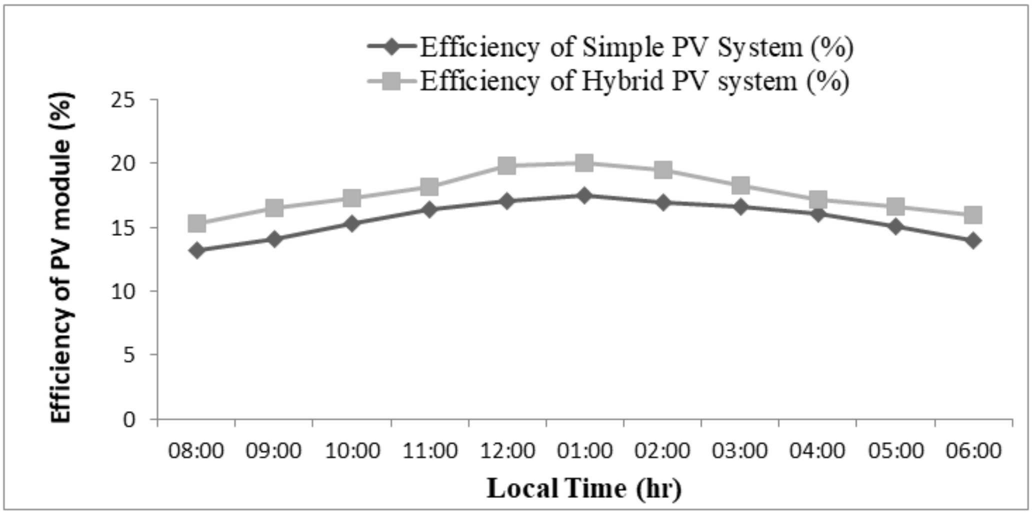

Figure 3.9: Graph of Relationship between the Efficiencies of simple PV and hybrid PV-TEG Systems

The result of the effect of cell temperature reduction on thermoelectric generators was presented in Figure 3.10 and it showed 0.12 W maximum TEG power outputs was achieved when the cell temperature reduced by 6.5ºC (from 65.4ºC to 58.9ºC) which is 9.94 % reduction compared to simple PV cell temperature. This highlighted that TEG generated power due to potential difference enhanced as a result of change in temperature from the hot to cold side of thermoelectric generator. The result in Figure 3.11 presented the relationship between overall power output and efficiency of Hybrid PV-TEG system. The reported maximum values of 11.67 W and 20.2 % of power output and efficiency respectively, highlighted that the power output generated by the thermoelectric generators integrated with PV modules, contributed to the overall systems power outputs and efficiencies.

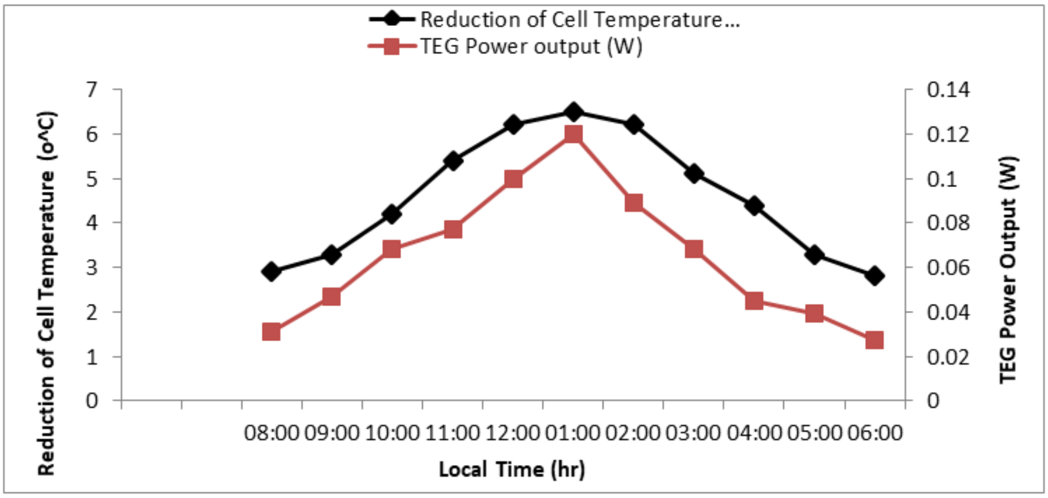

Figure 3.11: Graph of Effect of Temperature Reduction on TEG power output

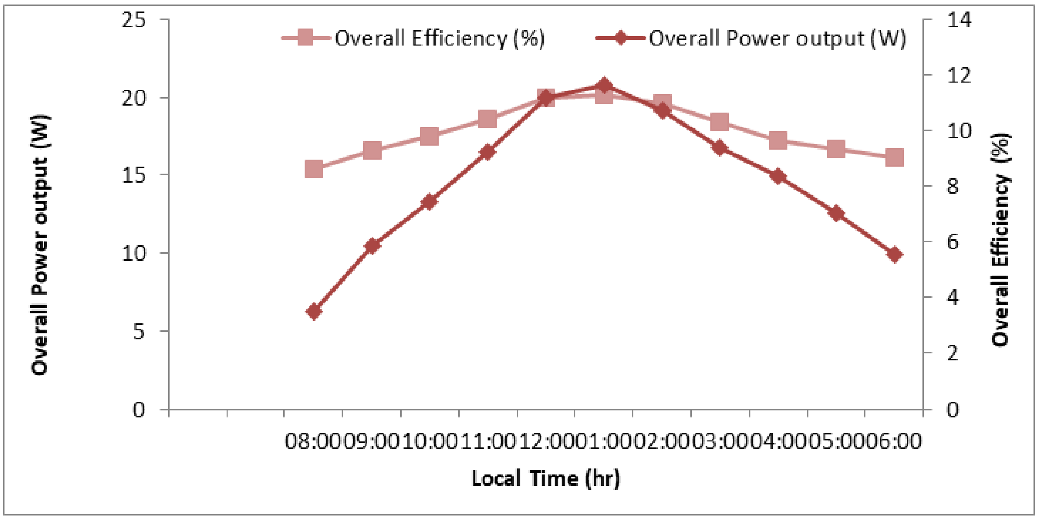

Figure 3.11: Graph of Relationship between the Overall Power Outputs and Efficiencies

The results of paired T-test for mean difference between the simple PV and hybrid PV transient power outputs predicted that at 95% confidence intervals, the mean deviation and the standard error mean for the hybrid PV have values 8.125±2.547 and 0.768 respectively, which are higher values compared with simple PV system. This resulted mean deviation difference of -0.953±0.373 and a standard error difference of 0.1225 and reported -8.46 T-values and 0.000 P-value. Also using the same paired T-test, the result of statistical analysis for the mean difference between efficiencies obtained from simple PV and hybrid PV systems were presented. The result from the hybrid PV systems showed mean deviation and standard error mean with values 17.7±1.59 and 0.479 respectively, which are higher compared to those from simple PV systems. This resulted to a negative man deviation difference of – 2.07±0.484 and a standard error mean difference of 0.1459 and however, reported a T-value and P-value of -13.89 and 0.000 respectively. Meanwhile, by comparing the overall statistical results between the parameters been considered, with the small P-values of (0.000) been observed has further suggested that the results are inconsistent with H_o, $\mu_d = 0$ that is the two parameters in each case does not perform equally. This also proved that there is significant increase of power output and efficiency on solar PV module by hybridizing with thermoelectric generator. Hence, a complete solar spectrum was conserved by hybrid PV-TEG system.

4.1 CONCLUSIONS

The performance analysis of the solar hybrid PV-Thermoelectric system for electricity generation has been investigated. The results confirmed that the transient current and voltage outputs from hybrid PV-TEG system were greater than those from simple PV system. The reduction in temperature observed on the rear side of the hybrid PV-TEG system enables enhancing higher current, voltage and power and efficiency compared to simple PV system. The statistical analysis confirmed the effectiveness of the results and inconsistency between the results obtained from hybrid PV-TEG and simple PV system. Therefore, solar PV system can be optimized by using thermoelectric generators for economical and reliable power generation.

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