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Case Study of Performance of Hybrid Solar Photovoltaic-Thermal Water Heating System in Sokoto, Nigeria

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Abstract: *The ambient temperature of northern Nigeria climatic condition is mostly about 30°C-45°C, it incites about 30°C-80°C heat over the panel since black body of the panel observe more heat, and this temperature majorly affect the electrical efficiency of the panel.Residential houses are constructed with limited space in Sokoto due to rising population; these spaces cannot install a separate PV panel for electricity generation and solar thermal for hot water production standing side by side. In order to resolve these problems, in this work, thermosiphonic water cooling is utilized to reduce the operating temperature of the PV module and then comparing its performance with a controlled PV panel.The PV/T system can be installed to lower the area requirements compared to the two separate systems of same capacity. Photovoltaic/thermal hybrid collectors are technology, which allows simultaneous harnessing of thermal energy and electricity from solar irradiance with a single system. Furthermore, the performance of the PV cells increase due to lower cell temperatures because of heat extraction. This research investigates the effect of cooling on the PV panel and analyzed the experimental thermal and electrical energy performance of the PV/T system for a sunny and cloudy day, then comparing the electrical performance of the PV/T to the controlled PV panel. Analysis of experimental result indicated that the electrical and thermal efficiencies during the sunny day are higher than during the cloudy day. It can also be drawn from the research that the average thermal and electrical efficiencies for the sunny day of experiment of the PV/T water heater is 33.45% and 8.61% respectively. The average electrical efficiency of the controlled PV module is 7.74%. It is also clear that the PV/T electrical performance is 0.87% greater than the controlled PV panel for the sunny day of experiment. From the result of the daily performance and total performance of the two systems, it is a clear fact that the electrical performance of the PV/T collector depends on the cooling effect of the PV panel by the fluid.*

Key Words: *Hybrid, photovoltaic-thermal, Water heater, photovoltaic module*

I. Introduction

The sun is the ultimate source for most of our renewable energy supplies and the direct use of solar radiation has a deep appeal to engineer and architect alike. Solar thermal collectors are used to convert solar radiation to thermal energy. In a thermal collector, a liquid or gas is heated and pumped, or allowed to flow through thermal convection, around a circuit and used for domestic or industrial heating. Photovoltaic cells are used to direct conversion of sunlight to electricity. The principal function of a PV cell is simple-silicon wafers convert the solar energy falling on them directly into electricity (Singh and Ravindra 2012). The most significant difference between solar thermal and photovoltaic system is that solar thermal systems produce heat and photovoltaic systems produce electricity. There are several methods to gather the solar energy and in a PV system most of the solar radiation that is absorbed is not converted into electricity. PV cells utilize a small fraction of the incident solar radiation to produce electricity and the remainder is turned mainly into waste heat in the cells, causing the increase of PV cell temperature hence the efficiency of the module drops. Cooling either by natural or forced circulation can reduce this PV cell temperature (Chow, et al., 2006). An alternative to the PV cell is to use Photovoltaic thermal system (PV/T) as in figure 1 below:

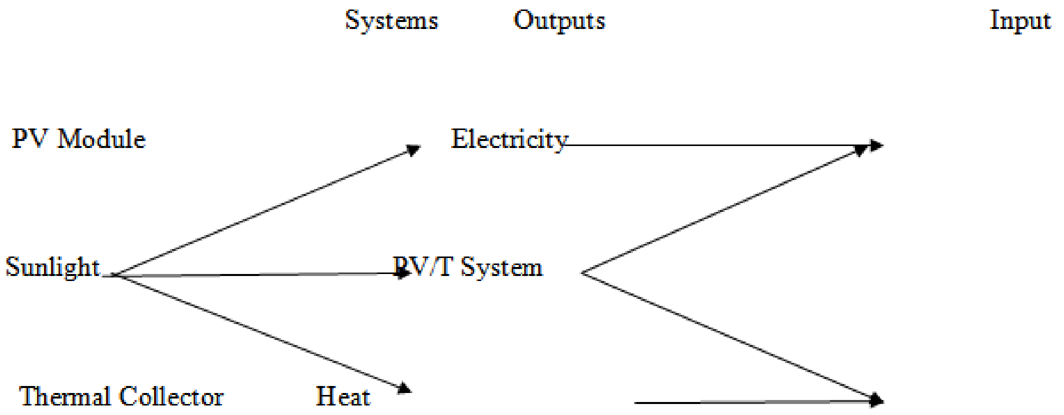

Figure 1: Overview of Solar Energy System

where PV cell is coupled with heat extraction devices. The simultaneous cooling of the PV Module maintains electrical efficiency at satisfactory level and thus the PV/T collector offers a better way of utilizing solar energy due to the increased overall efficiency (Colon, 2001). The attractive features of the PV/T system are:

• It is dual-purpose: the same system can be used to produce electricity and heat output;
• It is efficient and flexible: the combined efficiency is always higher than using two Independent systems and is especially attractive in BIPV when roof spacing is limited;
• It has a wide application: the heat output can be used both for heating and cooling (Desiccantcooling) applications depending on the season and practically being suitable for domestic applications;
• It is cheap and practical: can be easily be retrofitted/integrated to building without any major modification and replacing the roofing material with the PV/T system can reducethe payback period.

In order to reduce the impact of temperature on PV cell performance, various modifications have been attempted in the heat recovery channel of the PV/T system. In this research, emphasis will be on the development and performance analysis of a prototypemodel of a PVT system with natural circulation.

II. Methodology

The experiments were carried out under the meteorological conditions of Sokoto (latitude of 13º 05'N; longitude of 05º 15'E) in Nigeria, for two days (a sunny and cloudy day) from 9.00 a.m. in the morning to 5.00 p.m. in the evening. The PV/T system (experimental) and a photovoltaic panel (control) were used in this research to test and compare the performance of the PV/T system. Below is the specification of the two panels used as experimental and control group for this research:

Table 1: Specification of the two PV panels

PV Panels	Types	Power (w)	I_{sc}(A)	V_{oc}(v)	I_m(A)	V_m (v)	Length (m)	Width (m)	Area (m^2)
PV/T	Polycrystalline-Silicon	160	4.677	44.322	4.370	36.663	1.58	0.81	1.28
control	Polycrystalline-Silicon	160	4.677	44.322	4.370	36.663	1.58	0.81	1.28

Several devices were used to take measurements and characterize the performance of the collector, including six K-type thermocouples, a pyranometer, an anemometer, two multimeters for the PV/T system, another two Multimeter for the control group PV panel and a data logger (DL 2e). The six thermocouples are connected to the data logger, which displays the values ofeach temperature reading. Below is the schematic diagram of the experiment group and control group of the experimental equipment.

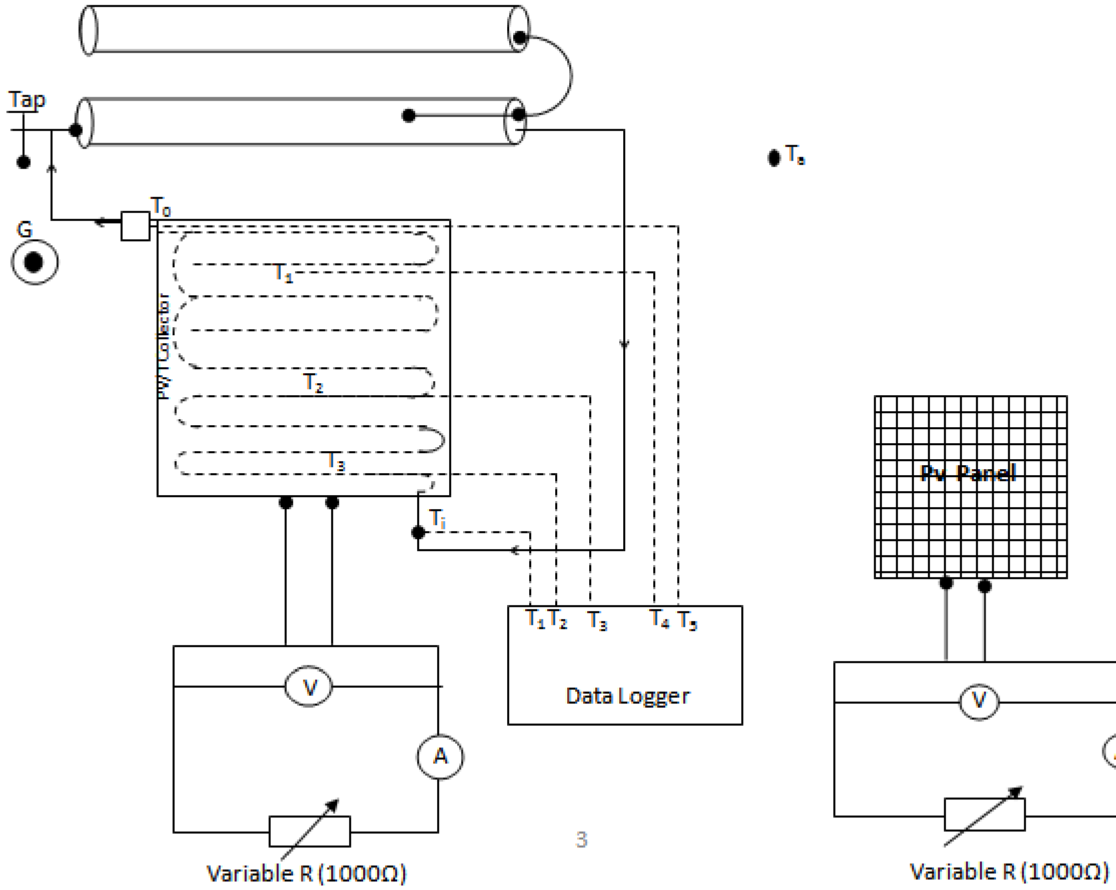

Figure 2: Schematic Diagram of the Experimental set up of the systems.

In order to characterize the thermal performance of the PV/T collector, temperature measurements was taken at various locations throughout the assembly. One K-type thermocouple mounted on the outside surface measured ambient temperature (T_a) from a multimeter, three K-type thermocouple embedded at three locations (two at extreme ends and one at the middle) of the absorber copper plate (T_1, T_2 and T_3) measured the interior copper plate temperature, an infra-red thermometer was used to measure the temperature of the PV surface at three different locations, and two K-type thermocouple inserted into the PVC plumb measured the water inlet and outlet temperatures (T_i and T_o). Each K-type thermocouple was connected to a data logger (DL 2e) which then displays the values of the temperature from each sensor in degree Celsius.

Table 2: Sensor and Data Acquisition Equipment

Type and Model	Measurement
Thermocouple Type K – T_1	Inlet temperature (^{0}c)
Thermocouple Type K – T_2	Outlet temperature (^{0}c)
Thermocouple Type K – T_3	Top end of the absorber plate temperature (^{0}c)
Thermocouple Type K – T_4	Low end of the absorber plate temperature (^{0}c)
Thermocouple Type K – T_5	Middle of the absorber plate temperature (^{0}c)
Infra-red thermometer (IR-260-8S)	PV surface temperature (^{0}c)
Digital Multimeter (DT 830)	Ambient temperature (^{0}c)
Pyranometer (CMP 3)	Solar irradiance (W/M^2)
Anemometer	Wind speed (M/S)
Digital Multimeter (DT 830)	Current, Voltage and Resistance (A,V and Ω)

Forming the remainder of the data collection suite are the anemometer, pyranometer and the multimeters. It was important to collect wind speed measurements to determine how wind influences the efficiency the PV/T system. An inspeed vortex anemometer mounted at the same plane with the PV/T system assembly measured wind speed as its head rotated and generated “clicks”. Insolation measurements were taken by a CMP-3 pyranometer mounted with the sensor in the same plane as the panel (G). Electrical readings from both PV/T and PV panels were taken by connecting a multimeter in series with the panels to measure current (I) and another multimeter was connected in parallel to the panels to measure voltage (V), all these are measured simultaneously for the PV/T and PV panels. Flow rate (m) through the thermal components of the PV/T panel was measured by allowing water to flow out of the system into a measuring cylinder for thirty seconds, measured by stopwatch, weighing the resulting volume of water, repeating the process five times, and calculating the average. The water flow rate was set close to $0.008 kgs^{-1}$ as possible and was not altered for experimental purpose.

III. Results And Discussion

3.1 Calculation of the PV/T Parameters

3.1.1 Thermal Parameters

Determining the mass flow rate of fluid M= dm/dt ($0.008\ kgs^{-1}$), the fluid temperature rise ($\Delta T = T_0 - T_i$) and thespecific heat of fluid C_p= 4180 J kg^{-1} $k^{-1}$for water. The thermal power output or Heat energy absorbed in 30 minutes for the projected area can be calculated by following relation;

$Q_u = M\ C_p(T_o - T_i)$ (1)

The thermal efficiency is determined as a function of the solar radiation (G_T), the input fluid temperature (T_i), and the ambient temperature (T_a). The steady-state efficiency is evaluated according to (Saad and Hosni, 2012):

$$\eta_{th} = \frac{MC_p(T_o - T_i)}{H A_c G_T} \quad (2)$$

Where $\eta_{th}$is the thermal efficiency; A_c is the collector area (m^2); T_o is the fluid outlet temperature (^0c); T_i is the fluid inlet temperature (^0c); m is the mass flow rate of the fluid (kg/s); C_p is the specific heat capacity (J/kg k); G_T is the irradiance on the collector surface (w/m^2).

3.1.2 Electrical Parameters

The characteristic V-I test was conducted on both the PV/T and controlled PV panels. The Rheostats were connected as avariable resistive load (R) with the panels separately and by varying the R value, the values of voltage and current are noted down. From the test values, the maximum power point was calculated with the equation below;

$Q_{el}(pvt) = I_m \bullet V_m$(3a)

$Q_{el}(pv) = I_m \bullet V_m$(3b)

The test was conducted on the panel 30 minutes once from 9:00 am to 5:00 pm daily.

The electrical efficiency depends mainly on the incoming solar radiation and the PV module temperature (Chow, T.T. et al., 2006). It is calculated with the following equation as given by (Saad and Hosni, 2012):

$$\eta_{el} = \frac{I_m V_m}{G_T A_c} \quad (4)$$

Here, $I_m$and V_m are the current and the voltage of the PV module operating under a maximum power.

3.2 Experimental Observations

The experimental observations of the hybrid PV/T and controlled PV panel were carried out within the month of May, 2014 for two days in order to study the thermal and electrical behavior of the system for a sunny and cloudy weather conditions. Of these two days observation, (sunny day, 12th, May 2014 and cloudy day, 19th, May 2014) are studied in this research. The experimental results on sunny and cloudy days are shown in figure 3 and 4 below:

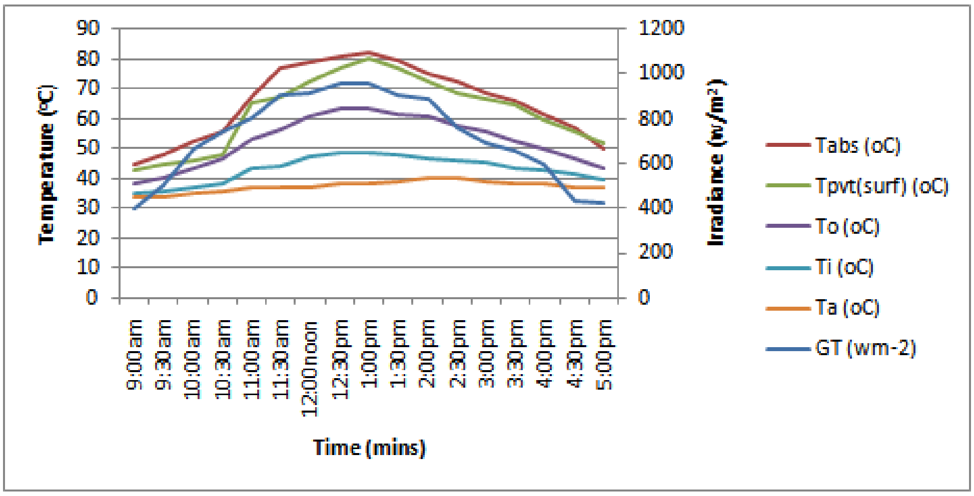

Figure 3: Time series of the monitored parameters on a sunny day (12th, May 2014)

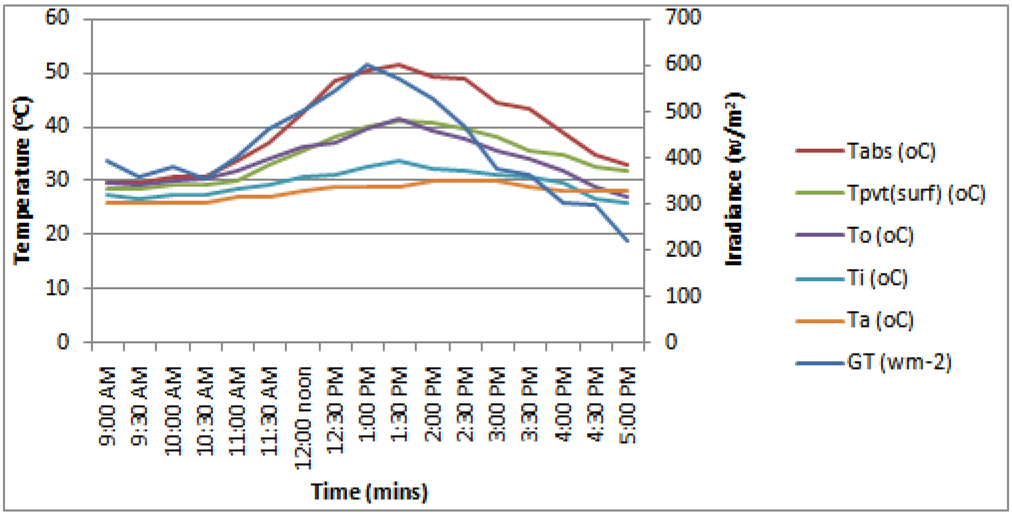

Figure 4: Time series of the monitored parameters on a cloudy day (19th, May 2014).

Figure 3 and figure 4 shows the trends of measured solar radiation, ambient temperature, inlet temperature, outlet temperature, absorber-plate temperature and PV/T surface temperature.Figure 3 show that the thirty minutes variations of the system temperature for sunny days gave a maximum outlet temperature of 63.2°C. This according to (Tiwari et al., 2009) is effective for most domestic and probably industrial needs where low pressure is required. Figure 3 however, indicates that maximum outlet temperature was reached between 12:30 pm to 1:30 pm for sunny days. Figure 4 shows the maximum outlet temperature for a cloudy day gave 41.6°C. This value is within the range reported to be effective for use as bathing and washing according to (Fugisawa and Tani.T, 1997). The ambient temperature and solar irradiance are also reported in figure 3 and 4. It can be seen in the figures above that the outlet temperature, absorber-plate temperature and PV/T surface temperatures vary as dependent on the solar irradiance conditions. Worthy of note is the fact that, when the maximum water temperature of 63.2°C for sunny days was achieved, the inlet temperature was 48.0°C. The difference in temperature of 15.2°C is the impact of the system on the inlet water. Moreover, (Tiwari et al., 2009) reported that, a system which can add temperatures between 10°C-30°C is adjudged to be effective. Based on this, the thermosyphon PV/T water heatingsystem of this study was found to be effective.

3.3 Thermal and Electrical Performance of the PV/T System on a Sunny and Cloudy Day

The PV/T Collector performance tests were conducted for two days with sunny and cloudy condition in the month of May. The PV/T collector slope was adjusted to 15^0, which is considered suitable for the geographical location of Sokoto (13^0 15′ N, $05^0$15′ E). The PV/T collector thermal and electrical (Q_u and Q_{el} (pvt)) power output were calculated using equations 1and 3a respectively.

The thermal and electrical outputs of the two systems for a sunny and cloudy day are recorded, and the variation of these outputs are shown in figures 5 and 6 below:

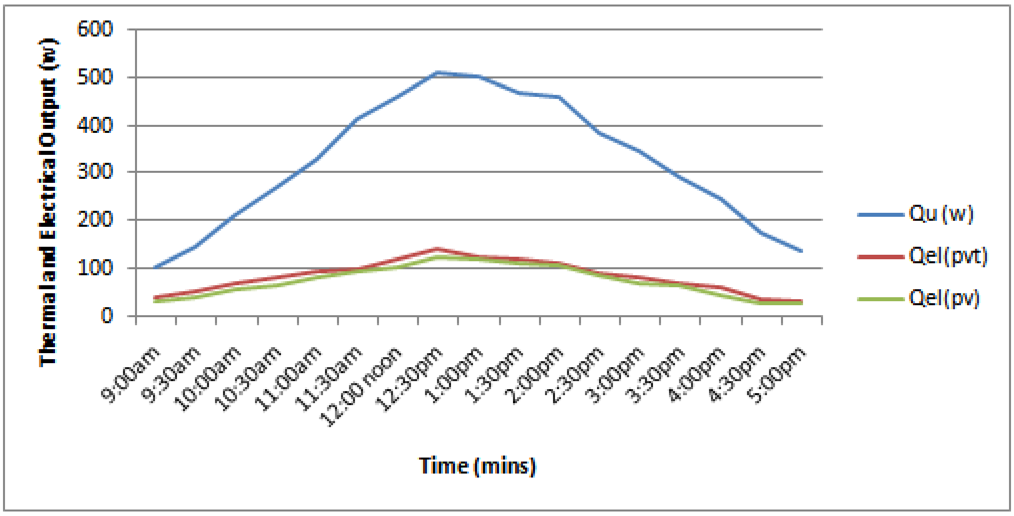

Figure 5: Variation of Q_u, Q_{el} (pvt) and Q_{el} (pv) vs. time for a sunny day (12th, May 2014)

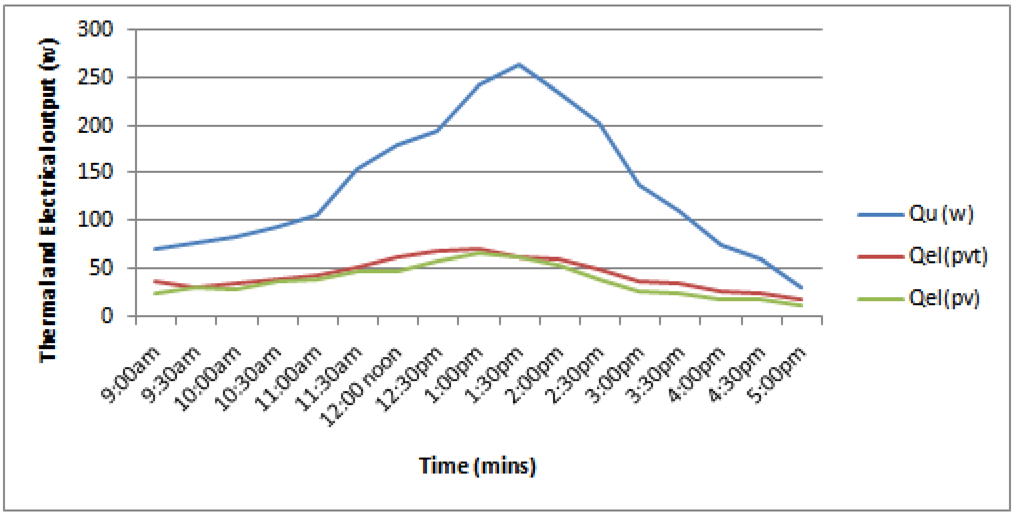

Figure 6: Variation of Q_u, Q_E ($_{pvt}$) and Q_E ($_{PV}$) vs. time for a cloudy day (19^{th}, May 2014

Figure 5 and 6 shows the variation of thermal power output and electrical power output for the PV/T water heater and the controlled PV system for a sunny and cloudy day. The three quantities correspond to each other whereby the maximum powers for the sunny and cloudy days are obtained between 12 noon and 2:00pm. The maximum thermal and electrical power outputs for the PV/T system are 509.5W and 140W respectively, and for the controlled PV module, the electrical power output was found to be 125.5W for a typical sunny day. The difference in the electrical power outputs of the PV/T and controlled PV systems was found to be 14.5W. This maximum thermal and electrical power outputs for a sunny day were obtained at the same hour of 12:30pm when the solar radiation was at its peak of 957wm^{-2} and ambient temperature of 38^{o}c.

The thermal and electrical power outputs of the PV/T water heater and the electrical output of the controlled PV module on a cloudy day are shown in figure 6. The maximum thermal and electrical power outputs for the PV/T system are 264.81W and 70.5W respectively, and for the controlled PV module, the electrical power output was found to be 65.8W for a typical cloudy day. The difference in the electrical power outputs of the PV/T and controlled PV systems was found to be 4.7W. The power outputs for the cloudy day were obtained at different hours. The maximum thermal power output was obtained at 1:30pm, the maximum electrical power outputs of the PV/T water heater and the controlled PV module were obtained at the same time of 1:00pm.The difference in time to obtain maximum thermal and electrical outputs is due to the variable cloud cover during the day. These maximum power outputs were obtained when the solar radiation for that day was between 600wm^{-2} and 570wm^{-2}.

IV. Conclusion

A comprehensive study is made to reveal the characteristics of PV/T collectors and methods to evaluate their performance. An important outcome of the research has been the completion of an experimental setup with all necessary instruments to test the performance of PV/T collectors and comparing the electrical performance of the PV/T collector to the electrical performance of a controlled PV/panel. Furthermore, the set up may also be used to perform thermal performance analyses on other types of collectors with small modifications.

It is observed that by combining thermal and electrical aspects of solar panels, an increase in electrical output is experienced due to the reason that the water circulation through the collector decreases the overall temperature of solar cells, which lead to a performance increase in terms of electricity production. This effect is experienced in the experiments that are conducted on the PV/T module, an increase in electrical output is recorded when there is a flow through the collector in comparison to the case where there is no flow through.

Finally, the economic and environmental analyses of the PV/T water heating system (though not studied in this work) could bring about daily and annual savings of fuel wood and CO_2respectively since the system can be used to heat water and produce electricity at the same time.

Fortunately, Sokoto in Northern Nigeria is blessed with an enabling environment with an average of 8 hours daily sunshine throughout the year. Therefore, supporting the usage of this new and viable sustainable alternative energy system would bring tripled benefits, socially, economically and environmentally. The system could reduce dependence on expensive finite fossil fuels, which could bring stability to the existingenergy supplies, save forests, reduce soil erosion, and results in better crop yields to farmers. It also reduces prevailing health issues (mostly affecting women and children), lung and eye diseases caused by smoky fires to mention but a few.

NOMENCLATURE

A_c Collector area, (m^2)
C_p Specific heat capacity of fluid, (j/kg/^{0}c)
G_T Intensity of solar radiation, (W/m^2)
I_m Current maximum power of the PV or PV/T panel (A)
I_{sc} Short circuit current (A)
K Thermal conductivity of insulating material, (W/m^2k)
k_1 Heat transfer coefficient (W/m^2k)
k_2 Heat transfer coefficient (W/m^2k)
M Mass flow rate of the fluid through the collector, (kgs^{-1})
Q Energy absorbed by collector in time, t (W)
Q_{el} (PV) Electrical output or rate of electrical energy extracted by the PV panel (W)
Q_{el} (pvt) Electrical output or rate of electrical energy extracted by the PV/T panel (W)
Q_u Thermal output or rate of heat energy extracted by the collector, (W)
T_a Ambient temperature, (^{0}C)
T_i Collector inlet water temperature (°C)
T_f Final temperature of water (^{o}C)
T_m Collector mean temperature (°C)
To Collector outlet water temperature (°C)
T_{pv} PV module temperature, (^{0}C)
$T_{PV/T}$ Operating temperature of the PV/T module, (^{0}C)
T_1 Temperature at the top end of the absorber plate (^{o}C)
T_2 Temperature at the middle of the absorber plate (^{o}C)
T_3 Temperature at the bottom of the absorber plate (^{o}C)
T_{abs} Temperature of the absorber plate (^{o}C)
V_{oc} Open circuit voltage
V_m Voltage maximum power of the PV or PV/T panel, (V)
ΔT Measurement of the temperature rise of fluid (^{o}C)
η Total efficiency ($\eta_{th} + \eta_{el}$)
η_{th}Thermal efficiency (%)
η_{el}Electrical efficiency (%)

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