IOSR Journal of Applied Physics (IOSR-JAP)
e-ISSN: 2278-4861.Volume 7, Issue 2 Ver. II (Mar. - Apr. 2015), PP 88-96
www.iosrjournals.org

Design and Construction of a Thermosiphonic Solar Photovoltaic-Thermal Water Heating System

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Abstract: *The maximum electricity conversion efficiency of the Solar Photovoltaic panel is 8-18% under the Standard Test Condition (STC) temperature of 25°C. The atmospheric temperature of Sokoto, North-West Nigerian climatic condition is mostly about 30°C - 45°C, it incites 30°C - 80°C heat over the panel since black body of the PV panel observe more heat, and this temperature majorly affect the electrical efficiency of the panel.A thermosiphonic solar PV/T water heating system which could be used for domestic purpose has been designed constructed and tested using locally available materials. Solar energy is received by the PV surface which then utilize a small fraction of the incident solar radiation to produce electricity and the remainder is turned mainly into waste heat in the cells, this waste heat is utilized by attaching an oscillatory flow heat exchanger brazed to a copper sheet and adhered at the back of the PV panel to extract heat from the PV panel, thereby increasing its electrical efficiency, and an insulated casing is placed at the back of the heat exchanger to reduce heat loss to the environment. A cold and hot water tank is then integrated to the system so that water flows from the cold water tank to the heat exchanger, gets heated and flows into a hot water storage tank through thermosyphon principle. Maximum fluid output temperature, solar insolation, thermal and electrical outputs are 63.2oC, 957W/m2, 509.5W and 140W respectively, were obtained on a sunny day. This solar water heating system finds useful application and acts as a renewable energy resource in regions where there is abundant and consistent sunlight.*

Keywords: *thermosiphon; PV/T; solar water heaters; solar energy; design and construction*

I. Introduction

A solar photovoltaic/thermal (PV/T) hybrid system is a combination of solar photovoltaic (PV) and solar thermal systems which simultaneously convert solar energy into electricity and heat from one integrated system. There are different approaches in PV/T system designing. The design parameters are based on collector type, thermal efficiency, electrical efficiency, solar fraction and operating temperature. There can be selections among air or water collectors, monocrystalline, polycrystalline, amorphous silicon or thin-film solar cells, glazed or unglazed panels, natural or forced fluid flow etc. In conventional photovoltaic system, high incident solar radiation on (PV) panel should give high electrical output. However, high incident will increase the temperature of the solar cells and that will decrease the efficiency of the panel. A PV/T collector consists of a PV module on the back of which an absorber plate is attached. The purpose of the absorber plate is to cool the PV module and thus improve its electrical performance and secondly to collect the thermal energy produced, which would have otherwise been lost as heat to the environment. This collected heat could be used, for low temperature applications. The hybrid design gives additional advantages, such as a reduction of the thermal stresses and hence a longer life of the PV module, high performance and reliability, low maintenance and a stabilization of the solar cell current–voltage characteristics.

Among the main works of last ten years on the liquid type hybrid systems are the presentation of the design and the results of a commercial type PV/T system (Elazari, 1998), the study of a system with cylindrical water storage tank (Huang, et al., 2001), the PV/T collectors with polymer absorber (Sandness and Rekstad, 2002) and the performance analysis of PV/T solar systems (Chow, 2003). The investigations on 1D, 2D and 3D models for PV/T prototypes with water heat extraction (Zondag, et al., 2003), the systems with water circulation in channels attached to PV modules (Coventry and Lovegrove, 2003) and the developed systems for domestic applications (Leenders, 2000), are the most important recent works on water cooled PV/T systems.

Design concepts, prototype construction and test results for water and air-cooled PV/T systems have been presented by the University of Patras (Tripanagnostopoulos, et al., 2002), where PV/T systems with and without additional glass cover are experimentally analyzed. In the same work the concept of using stationary diffuse reflector to increase the total energy output, instead of specular reflector, is also suggested. The dual type PV/T system, operating either with water or air heat extraction (Tripanagnostopoulos, 2001), the economic analysis that compares water cooled PV/T systems with standard PV and thermal systems (Tsepilis and Tripanagnostopoulos, 2002) are some additional works on water cooled PV/T solar systems.

In this paper we present the design and construction for hybrid Photovoltaic/Thermal systems in Sokoto, North-west Nigerian weather that use water as heat extraction fluid, providing electricity and hot water. The suggested systems are analyzed regarding the design concepts, the electrical and thermal conversion effect for different PV module technologies and alternative heat extraction modes, the size of the hot water storage tank and the circulation modes, the necessary electronic devices and other components as well. The study is focused to small size PV/T water systems that can be applied to one family house, and can be used alternatively to the widespread flat plate thermosiphonic solar systems.

II. Materials And Methods

2.1 System Design

The domestic solar PV/T water heating system has been divided into thermal component and electrical component. The thermal component comprises storage tank, absorber plate and fluid passage pipes which converts the solar radiation into heat while the electrical component comprises the solar photovoltaic panel which converts the solar radiation into electricity. Solar PV/T water heater is a system designed to provide improved electrical efficiency and in addition provides hot water. These two provisions form the basis for design criteria and material selection, that is, the collector type and heat exchanger or heat removal mechanism.

2.1.1 The Solar Collector

As a result of the required system's output, that is, the provision of improved electrical power and thermal energy, a polycrystalline silicon module was selected and used as a collector for the purpose of this research, it has the following specification:

Table 1: Specification of the two PV panels

PV Panels	Types	Power (w)	Isc(A)	Voc(v)	Im(A)	Vm (v)	Length (m)	Width (m)	Area (m2)
PV/T	Polycrystalline-Silicon	160	4.677	44.322	4.370	36.663	1.58	0.81	1.28
Plate	Copper	-	-	-	-	-	1.50	0.76	1.14

It is required to design a system that will raise the temperature of 64 liters of water from an ambient temperature of 280C to 650C within a working day of the collector.

Energy gained by water; given by (Incropera and Dewitt, 1996)

$$Q = \rho_w v C_p \Delta T \quad (1)$$

Energy absorbed by collector in time, t; given by (Incropera and Dewitt, 1996)

$$Q = c G_T A_c t \quad (2)$$

Thus, Energy gained by water = Energy absorbed by collector in time,

Therefore, $\rho_w v C_p \Delta T = c G_T A_c t$;

And, $A_c = \rho_w v C_p \Delta T / c G_T t$

Average solar insolation in North-West Nigeria is 670w/m2 (Data from Sokoto Energy Research Centre, UDUS). Considering a collector efficiency of 65% and daily heating period of 8 hours; Ac = [1000 X 90 X 10-3 X 4190 X (65 - 28)] / [0.60 X 670 X 8 X 3600] = 1.21m2. Hence, 1.28m2 was used as the area of the absorber collector.

2.1.2 The Cold and Hot Water Tank

Volume of cylindrical cold water tank = $\pi r^2 l$, where π = 3.142, r = 0.155m and l = 1.21m.Therefore volume of the cold water tank = 3.142 X 0.155 X 0.155 X 1.21 = 0.091m3 = 90 liters.

The hot water tank is a cylindrical double walled tank with insulation material in-between. This is similar to the cold water tank but the volume of water in the hot water tank differs to the volume of water in the cold water tank. This is because a WC ball valve was inserted at the top end of the hot water tank to maintain the water level in the hot water tank to a certain level for easy thermosiphonic action to take place.

Volume of water in the hot water tank = $\pi r^2 l$, where π = 3.142, r = 0.12m and l = 1.21m

Therefore, volume of water in the hot water tank = 3.142 X 0.13 X 0.13 X 1.21 = 0.064m3 = 64 liters.

This value is agreed by (Adegoke and Bolaji, 2000), that for a better performance of a thermosyphon water heating system, every 1m2collector area should raise a tank of 60-90 liters capacity. Hence, 64 liters water tank capacity for the 1.28m2collector area.

2.1.3 Pipe Spacing and Sizing

The effect of tube spacing as a design factor in the performance of a natural-circulation solar water heater for copper was investigated by: (Agbo, and Okeke, 2007). The collector performance in terms of the collector efficiency and the collector fin efficiency are both obtained theoretically, experimentally and by a computer-aided simulation based on the Hottel-Whiller model of the system. The result indicates that the tube spacing varies inversely with both the collector efficiency and the fin efficiency for the copper absorber plate. Performance is optimized with a tube spacing not exceeding 12 cm. Spacing between pipes was chosen to be 11cm. The statement above and value of Agbo and Okeke is in line with the value (0.11m) used for tube spacing in this research. Because copper plate is used in this research, a copper pipe was chosen, whose diameter is ½" (1.27cm), thickness of 2.5mm, overall length of 118cm and pipe spacing of 11cm.

2.1.4 Insulation Thickness

Using Fourier's law of heat conduction, insulation thickness of the hot water tank is calculated as given by (Rajput, 2002):

For cylindrical vessels, heat loss per unit time;

$$Ql = 2\pi l(Tf - Ta) / [\ln (r2/r1) / K + 1 / h0\, r] \quad (3)$$

Where Tf and Ta are final and ambient temperatures of the water and r2 and r1 are radii of outer and inner hot water tank respectively; h0 is the convective heat transfer coefficient of outer tank; K is the thermal conductivity of insulating material.

Heat gain by water, $Q = m\, Cp\, (Tf - Ti)$

Where m is mass of water; Ti is initial temperature of water; Cp is the specific heat capacity of water at constant pressure.

Heat loss by tank = Heat gain by water;

$2\pi l\, (Tf - Ta) / [\ln (r2/r1) / K + 1 / h0\, r] = m\, Cp\, (Tf - Ti)$

Substituting values; h0 = 0.96 W/m2 K

Critical radius of insulation, rc = K / h0 = r2 (Rajput, 2002)

rc= 0.053 / 0.96 = 0.055m, thus, chosen thickness of insulation = 5.5cm. Hence, 5cm insulation for the hot water storage tank was used.

Construction

For the purpose of testing the PV/T collector, the oscillatory copper tube from a long copper pipe of 1/2 inch diameter was constructed and then adhered at the back of the copper sheet by brazing. The adhered copper sheet and tube was then attached to the back of the PV panel. A sheet of foam of ¾" or 0.019m thickness and ply-wood of ¼" or 0.0064m thickness was cut according to the size of the back of the PV panel and placed in the frame behind the solar thermal component in order to thermally isolate the heat transfer medium. Two cylindrical tanks (hot water tank and cold water tank) were constructed. The hot water tank was a double walled tank, insulated with a Styrofoam of about 5cm thickness between the double walls. The cold water tank was a single walled tank without insulation. Both tanks were constructed with a G.I sheet of 22 gauges. The mounting frame was constructed with a number of metallic angles by welding method on which a number of units like the storage tank (hot and cold water tanks) and the solar PV/T collector are mounted. A WC ball valve made of plastic was inserted in the hot water tank; this is not to allow water in the hot water tank to fill up to the brink for easy thermosiphonic. This WC ball valve connects to the cold water tank with a ½" or 0.0127m PVC pipe.

Experimental Testing

The PV/T system was installed and test was conducted at the testing ground of Sokoto Energy Research Centre, Usmanu Danfodio University Sokoto (Nigeria) which is located at 050 15′ E longitudes and 130 05′ N latitude. Due to the short amount of time available for testing, extensive parametric analysis was not possible, but a wide range of weather conditions typical of North-West, Nigerian summer seasons, from cold and cloudy to hot and cloudless days due to the range of time used for the experiment (that is, at the beginning of rainy season) provide a reasonable sampling of climate variation. The PV/T collector was oriented South with tilt angle of 130, which received the maximum solar radiation. The PV/T performance testing procedures followed the European standard and the PV/T performance measurement guidelines of the EN 12975-2 (Zondag et al., 2005). The measurements were recorded for eight hours from 9:00am to 5:00pm for seven different days.

The quantities measured during each experiment were:

• Global solar radiation intensity on the PV/T collector plane tilted at an angle of 150 to the horizontal, with a pyranometer that has a sensor to measure solar irradiance G, on a planar surface in W/M2.

• The two ends and middle of the absorber plate temperature (T1, T2, T3) in 0c, the inlet temperature (Ti) and the outlet temperature (To) all in 0c were measured with K-type thermocouples. All thermocouples were then connected to a data logger which displays the temperature values in 0c.

• Wind speed (v) in m/s was measured with an anemometer. The anemometer was placed 3m above ground level.

• Voltage, current and resistance are measured from the PV with digital Multimeter

Figure 1: Relief photo of the experimental set up of the experimental and control group

A – Cold water tank
B – Hot water tank
C – Hot water outlet
D - Multimeter
E – Variable resistor
F - Pyranometer
G - Data logger
H – Cold water inlet
I – PV module

2.4 Calculation of the PV/T Parameters

2.4.1 Thermal Parameters

Determining the mass flow rate of fluid M = dm/dt (0.008 kgs-1), the fluid temperature rise (ΔT = T0 -Ti) and the specific heat of fluid Cp = 4190 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;

Qu = M Cp (To - Ti) (4)

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

$$\eta_{th} = \frac{MC_p(T_o - T_i)}{A_c G_T} \quad (5)$$

Where ηth is the thermal efficiency; Ac is the collector area (m2); Tois the fluid outlet temperature (0c); Ti is the fluid inlet temperature (0c); m is the mass flow rate of the fluid (kg/s); Cp is the specific heat capacity (J/kg k); GT is the irradiance on the collector surface (w/m2).

2.4.2 Electrical Parameters

The characteristic V-I test was conducted on both the PV/T and controlled PV panels. The Rheostats were connected as a variable 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;

Qel(pvt) = Im • Vm (6a)

Qel(pv) = Im • Vm (6b)

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):

$$\eta_{el} = \frac{I_m V_m}{G_T A_c} \quad (7)$$

Here, Im and Vm are the current and the voltage of the PV module operating under a maximum power.

III. Results And Discussion

3.1 Experimental Observations

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

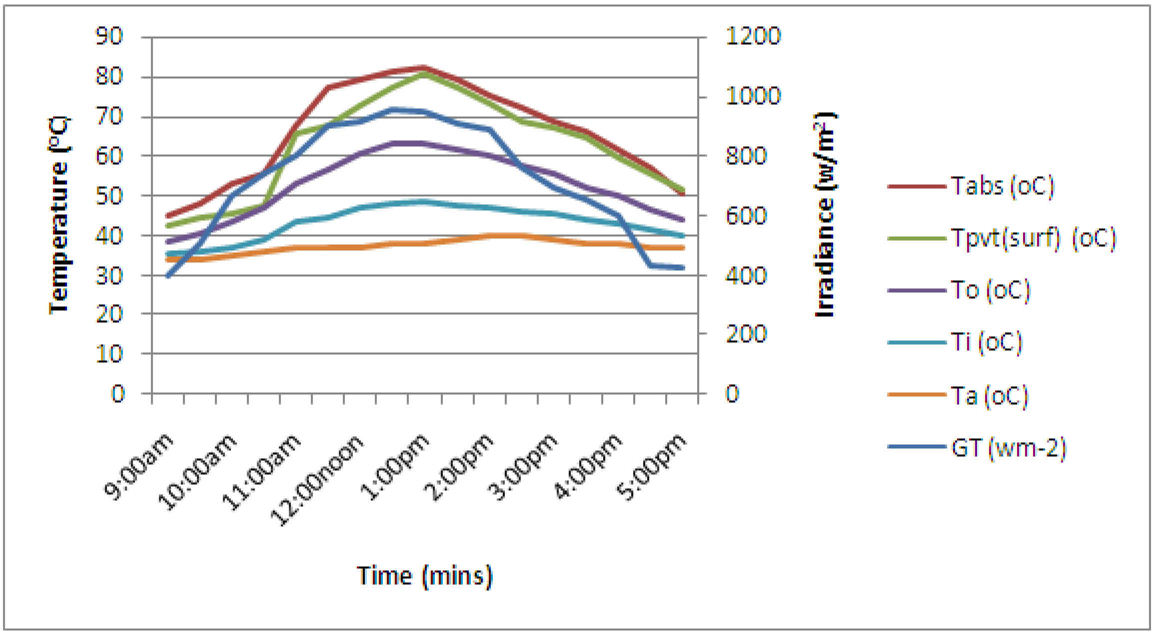

Figure 2: Time series of the monitored parameters on a sunny day (12th, May 2014)

Figure 2 shows the trends of measured solar radiation, ambient temperature, inlet temperature, outlet temperature, absorber-plate temperature and PV/T surface temperature.It can be seen in the figure 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 63.2oC for sunny day was achieved, the inlet temperature was 48.0oC.

The absorber plate temperature (T1, T2 and T3) as shown in figure 3, at the same height from the bottom of the collector (which is kept tilted) is noted continuously throughout the days of experiment. T1, T2 and T3 are the temperatures of the copper plate in the top, middle and bottom, respectively. The time-dependent variations of these temperatures for a sunny day are shown in figures 3 below:

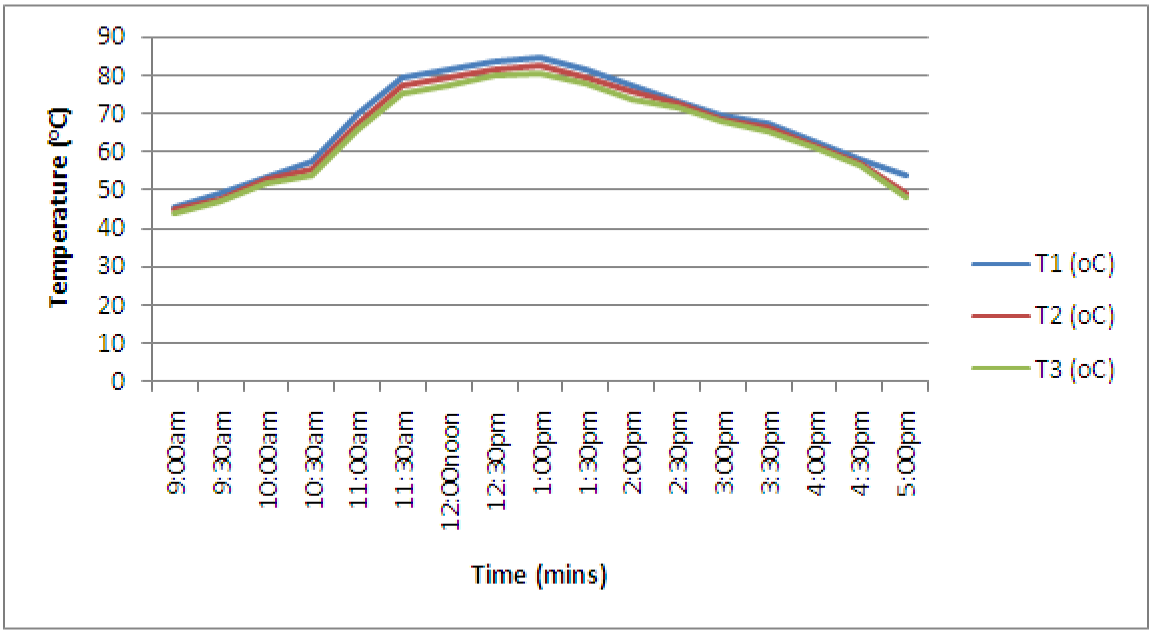

Figure 3: The variation of absorber plate temperature with time, with water flow on a sunny day (12th, May 2014)

From figure 4 above, it can be seen that T1, T2 and T3 are almost the same at any instant of time. However, a slight difference is observed during the hours when the thermosyphon mode is working. This also corresponds to the PV/T surface temperatures at TPV/T1, TPV/T2 and TPV/T3.

3.2 Thermal and Electrical Performance of the PV/T System

The PV/T collector thermal and electrical (ηTh and ηel) efficiencies were calculated using equations (5) and (7) respectively. The variation of the efficiencies on a sunny day is shown in figures 4 below:

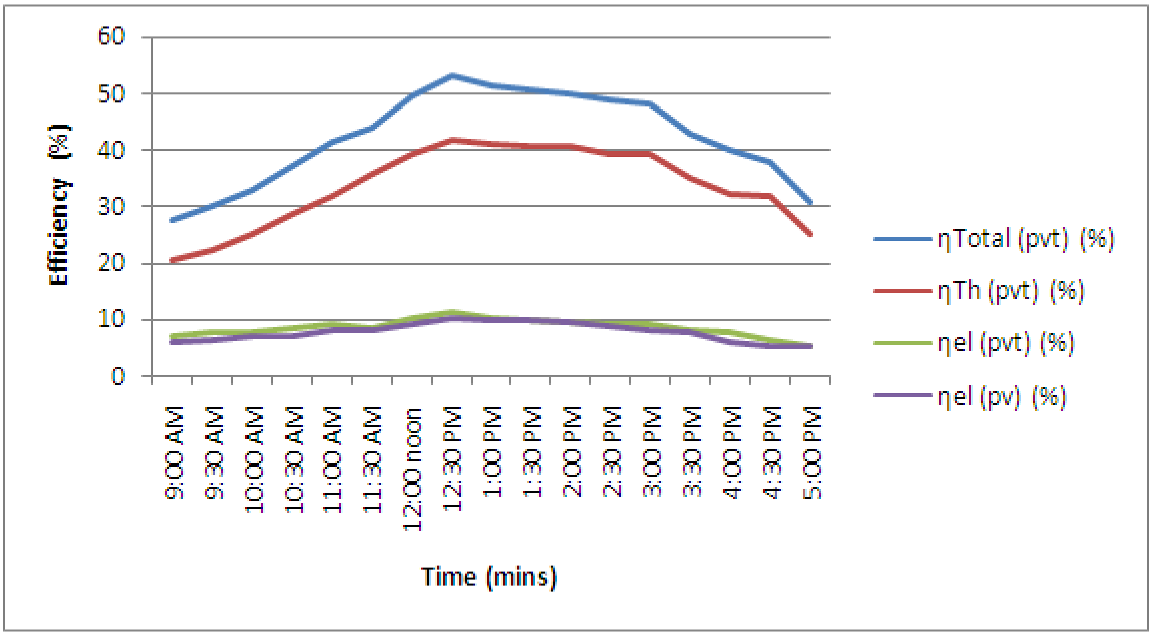

Figure 4: Variation of ηTh (pvt), ηel (pvt), ηTotal and ηel (pv) Vs. time for a sunny day (12Th, May 2014

Figure 4 shows the variation of total efficiency (thermal + electrical efficiency), thermal efficiency of the PV/T system, electrical efficiency of the PV/T system and electrical efficiency of the controlled PV module versus time for a sunny day. The maximum thermal and electrical efficiency of the PV/T water heater for a sunny day are 41.6% and 11.4% respectivey which gives a total efficiency of 53.0%. The maximum electrical efficiency of the controlled PV module for the same sunny day was found to be 10.3%. The above results showed that when the solar radiation increased, the electrical output also increased along with temperature for the sunny day.

3.3 Daily Performance and Comparison of the PV/T Water Heater and Controlled PV Module
A daily average measured and calculated parameters observed during the experimental tests for the seven days in May 2014, is presented in this section. In this case, the definition of daily means the hours used for a particular day to collect data.

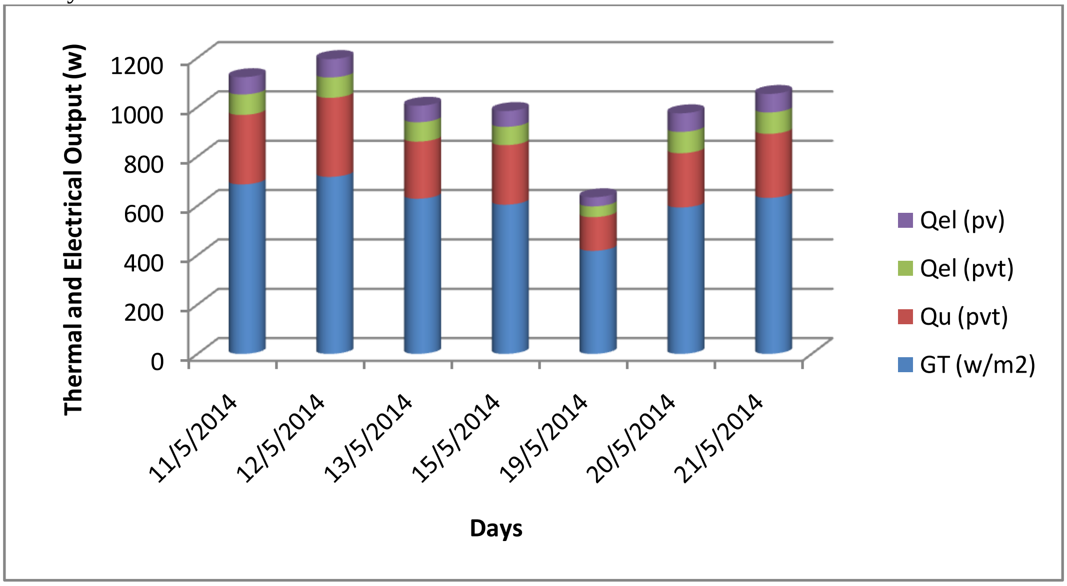

Figure 5: Input solar radiation, thermal and electrical output yield over seven days

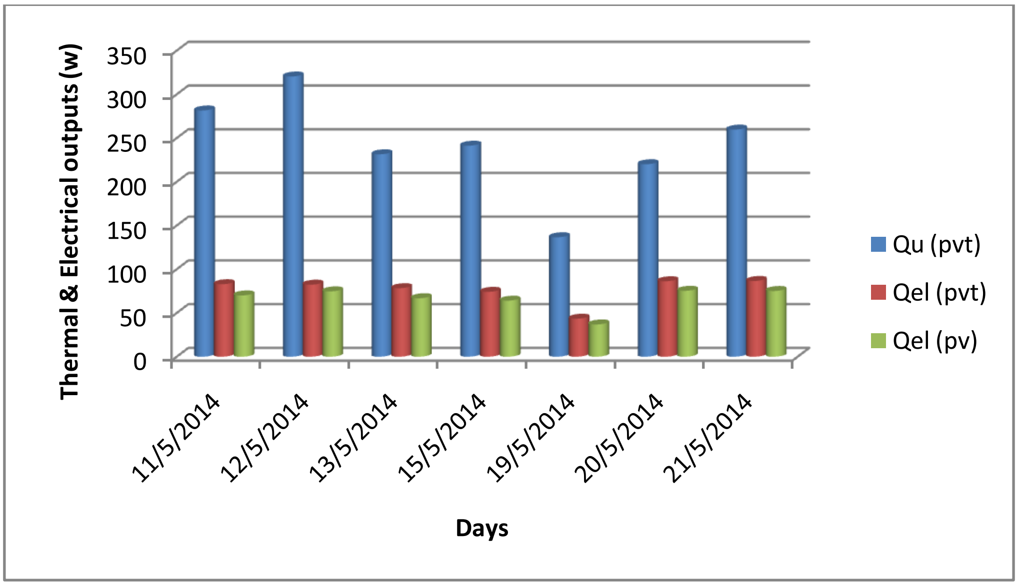

Figure 6: Daily average thermal and electrical output yield of the PVT and control PV system

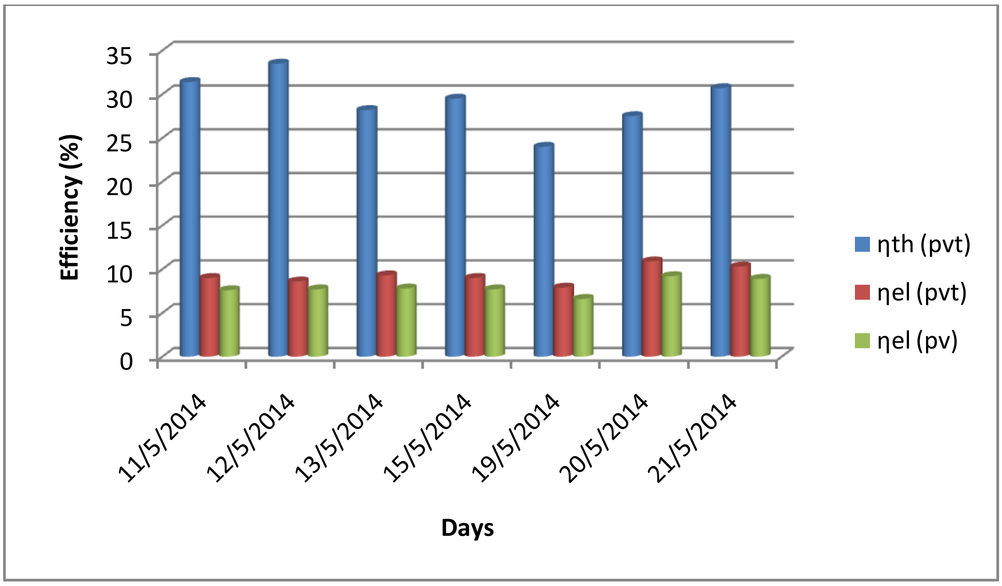

Figure 7: Daily average thermal and electrical efficiency of the PV/T water heater and the controlled PV module.

The average solar power input over the seven days of experiment is displayed in figure 5. The electrical and thermal energy produced by the system are also given. Figure 5 also shows the incident solar power for those seven days which means that according to the solar power input information, the power output of thermal and electrical can be estimated.

Figure 6 shows that a large amount of thermal energy was generated during the operation of the PV/T system, and this also shows that the thermal energy can be utilized in other aspects like, domestic and industrial use. Due to the meteorological condition, the solar radiation at Day 19th, May 2014 was much lower than the rest of days and this was also reflected on the energy output in thermal and electrical aspect. Figure 6 shows that the peak of electrical energy output occurs on the 20th and 21st May 2014 while the peak of thermal energy output occurs on the 11th and 12th May 2014. This can be attributed to the meteorological conditions on those days. For the peak electrical energy, it is as a result of high wind speed which was able to cool the surface of the PV and PV/T systems while for the peak thermal output energy, it is as a result of high solar radiation and ambient temperature. Therefore, it can be concluded that under the proper function of the system, the output energy can be generated proportional to the solar power input.

The efficiency of the system shown in figure 7 indicates that the electrical efficiency seems to be more stable than the thermal efficiency. The average electrical efficiency of the PV panel range is around 6.6%-9.2% while for the PV/T module range is around 7.9%-10.9%. From the graph, it can be easily seen that the thermal efficiency fluctuates significantly, unlike electrical efficiency. The reason could be that the thermal efficiency is a function not only of solar irradiation but also of the ambient temperature, heat losses to the surrounding and other meteorological parameters. Due to those factors, the variation of the thermal efficiency of the system is understandable. It can be concluded that the overall efficiency of the PV/T system is much higher than the PV system. This is also implied that the PV/T system can adequately harness the solar energy.

IV. Conclusion

A solar PV/T water heater is a long-term investment that can help us save money and energy for many years. Like other renewable energy systems, solar PV/T water heaters minimize the environmental effects of enjoying a comfortable, modern lifestyle at reduced costs because they do not have the hazards introduced by fossil fuels but are environmentally friendly and almost completely running cost free. The system designed in this work requires little or no maintenance because of the thermosyphon principle involved. It was made basically from locally available raw materials. It has no moving parts and almost the entire system works automatically, but there are some procedures to carry out to ensure proper functioning of the solar water heater and thus increase electricity savings:

(1) The solar module surface should be cleaned regularly to remove dust and dirt that may have settled on the glass cover which will block the sun rays and will reduce the output of the system. Depending on the surrounding where it is kept, it is advisable to clean two or more times a week.

(2) Prevent any shade on the collector. Trim the branches of trees around the collector to allow as much sunlight to reach it.

(3) Ensure that there is always cold water supply to the tank and flush out the entire system to remove any floating and settled dirt at least once in a year.

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