Design and Characterization of a Hybrid Flat Plate Photovoltaic-Thermal System

Nyariki Ondara Wycliffe, David M. Mulati and David M. Maina

Abstract- A variety of solar energy systems have been designed to harness sun power to produce both thermal and electric energy. Hybrid photovoltaic /thermal (PV/T) solar systems can concurrently provide electric energy and heat, thereby ensuring a higher conversion rate of the absorbed solar radiation. With proper designing, the PV/T systems can minimize the temperature effects on efficiency of a PV module by cooling it. In this paper, we present TRNSYS simulation results for a hybrid PV/T system for domestic water applications for a typical Kenyan family of five. Further, the results of the constructed PV/T system as predicted by the simulations are outlined and discussed. The PV/T system was constructed from polycrystalline silicon module available in the Kenyan market and coupled with water heat extraction unit. The resultant PV/T system was found to meet 47% of the hot water demand for family of five. With a payback period of 5.2 years, the PV/T system gives a lifetime cost saving of about Kshs.85941. The combined system efficiency range is between 37 and 62%. These figures are quite promising and they indicate that the PV/T system can be economically viable for a typical Kenyan household of five persons especially when electricity and hot water are required for domestic applications.

Keywords: *Hybrid; Photovoltaic; Solar Thermal.*

I. INTRODUCTION

A photovoltaic/thermal (abbreviated as PV/T) collector is a combination of a photovoltaic module on top of a thermal collector. The main reason of combining the two into a single unit is due to the benefits accrued. These benefits include higher energy per square meter of surface area, architectural uniformity on the roof, increased effective life of PV modules and lower manufacturing and installation costs. Due to these advantages, a lot of efforts in research have sought to improve this technology and make it more efficient and cost effective for wider applicability. Thus, various research activities in the last two decades have mainly focused in lowering the overall PV/T system cost and making it more efficient. This paper outlines the major publications on developments made in developing the PV/T collector.

Chow (2010) reports that main concepts of PV/T systems have been published for the past two decades. The author explains that various research studies and design concepts have been evaluated to determine which combined PV-thermal collector gives the best yield. Various researchers focus on various aspects of the system components with the main aim of realizing improved efficiency and cutting on costs of the overall system.

Various concepts of combined PV/T collectors are possible and they differ in the designer's approach to obtain maximum yield. Zondag et al. (2003) evaluated the yield of nine different flat plate PV/T designs to establish the expected yield of various concepts. The nine design concepts were grouped into four categories; sheet & tube PV/T collectors, channel PV/T collectors, free flow PV/T collectors and two absorber PV/T collectors. Further, the sheet and tube collectors were such that they had zero, one or two covers (glazing plates).

Design configuration influences the combined efficiency of a PV/T system. Ibrahim et al. (2009) investigated seven new design configurations of a flat plate PV/T collector with the aim of comparing the various configuration concepts. In their research, various design configurations were simulated to determine which configuration gives the best combined efficiency. Various parameters were used to analyze the system which included solar radiation, ambient temperature and flow rate conditions. The configurations included direct flow, oscillatory flow, serpentine flow, web flow, spiral flow, parallel serpentine flow and modified serpentine flow as illustrated in appendix A. From the simulations, spiral flow gave the highest output temperature followed by modified serpentine-parallel flow, parallel serpentine flow, direct flow, web flow, oscillatory flow and lastly serpentine flow. It was concluded from the simulations that the most efficient PV/T collector is the spiral flow design configuration, which gave a thermal efficiency of 50.12% and a corresponding cell PV efficiency of 11.98%. The study also observed that the spacing between the pipe runs play a pivotal role in a design configuration, and thus zero tolerance gap between pipes results in a more efficient PV/T collector.

PV/T systems are always installed on rooftops of residential buildings. To investigate their actual behaviour in service, Ji et al. (2003) installed a 40m^{2}PV/T collector on residential building's façade in Hong Kong. Under similar weather conditions, a PV/T collector made from thin film silicon gave a thermal efficiency of 48% whereas a PV/T collector made from crystalline silicon gave a thermal efficiency of 43%. They concluded that PV/T systems have a huge potential especially for a sub-tropical city such as Hong Kong.

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The geometric flow rate of the fluid through the absorber tubes greatly influences the overall performance of a PV/T system. In his research to determine the effect of flow rate on efficiency, Chow (2010) established that when flow rate in the absorber tube increases from 0.001 to 0.0075kg/s both thermal and electrical efficiencies increased. Further, Garg and Agarwal (1995) used the finite difference method to study the PV/T system with various solar cell areas and flow rates. They established that for maximum thermal efficiency, the optimum flow rate is 0.03kg/s. It was also shown that at this optimum flow rate for maximum thermal efficiency, electrical efficiency decreased and was at a minimum when the solar insolation was at a maximum.

II. PHOTOVOLTAIC-THERMAL COLLECTOR CHARACTERISTICS

Analyzing a solar energy system is a complex endeavor given the various predictable and unpredictable parameters. Modelling and simulation procedures are commonly used to aid the design process since they can give an optimum model before fabricating the prototype.

Florschuetz (1979) published the first mathematical model of a PV/T collector. In his study he modified the Hottel-Willier (1958) analytical model for a flat plate thermal collector in order to apply the equations to PV/T collectors. The equations are modified and adjusted properly in order to include the added section of the photovoltaic. These equations lead to the accurate calculation of the heat removal factor (F_R) and overall loss coefficient of the PV/T collector.

The performance of PV/T collectors is depicted by a combination of thermal and electrical efficiency. The total efficiency (η)is used to evaluate the overall performance of the system.

$$\eta = \eta_t + \eta_e \qquad (1)$$

Where $\eta_t$and $\eta_e$represent thermal and electrical efficiency respectively.

The thermal performance of the PV/T collector is affected by many system design parameters and operating conditions. In simulation, the system is analyzed with various configurations of solar radiation, ambient temperature and flow rate conditions. It is also assumed that the collector is represented as a flat plate thermal collector with a single glazing sheet. The performance of the PV/T unit is evaluated for its thermal and photovoltaic performance; as such the derivation of the efficiency parameters is based on the Hottel-Whillier equations (Hottel, 1958). This is illustrated in equation 2;

$$\eta_e = \eta_r[1 - \beta(T_C - T_r)] \qquad (2)$$

The thermal efficiency of the conventional flat plate solar collector is calculated using the formula:

$$\eta_t = \frac{\text{Useful output}}{\text{Solar input}} = \frac{Q}{G} \qquad (3)$$

where Q is the actual useful heat gain by the fluid through the absorber tubes and G is the measured incoming solar-irradiation on the collector surface.

Under these conditions, the useful collected heat ($\dot{Q}$) is given by:

$$\dot{Q} = \dot{m}C_P(T_a - T_i) \qquad (4)$$

where$\dot{m}$is the mass flow rate of the fluid through the absorber tubes, C_P is the specific heat of the collector cooling medium, $T_a$is the ambient temperature and $T_i$is the fluid inlet temperature.

According to Ibrahim (2009) the difference between the absorber solar radiation and thermal heat losses is given as:

$$\dot{Q} = A_C F_R[S - U_L(T_i - T_a)] \qquad (5)$$

whereA_C is a function of the collector area, $F_R$the Heat removal efficiency factor, Sis the absorbed solar energy, and U_L is the overall collector heat loss coefficient.

S is given as:

$$S = (\tau\alpha)_{PV} G_T \qquad (6)$$

$(\tau\alpha)_{PV}$is the average transmittance-absorptance of the collector and$G_T$is the solar radiation at NOCT (irradiance level 800 W/m^2, wind velocity 1 m/s, ambient temperature 26°C).

The heat removal efficiency factor F_R can be calculated as:

$$F_R = \frac{\dot{m}C_p}{A_C U_L}\{1 - \exp[-\frac{A_C U_L F'}{\dot{m}\ C_p}]\} \qquad (6)$$

The corrected fin efficiency F' is calculated using

$$F' = \left[\frac{1}{U_L\,(d_h + (W - d_h)F)}\right] + \frac{1}{Cb_{PV}} + \frac{1}{2(a+b)_{h_{fi}}} \qquad (7)$$

where d_h is the hydraulic diameter, w is the tube spacing, $Cb_{PV}$is the conductance of the bond between the fin and square tube, and $(a+b)_{h_{fi}}$ is the heat transfer coefficient of the fluid.

The efficiency factor F is then calculated as:

$$F = \frac{\tanh[m(\frac{w - d_h}{2})}{\sqrt{m\,(\frac{w - d_h}{2})}} \qquad (8)$$

where$m = \sqrt{\frac{U_L}{K_{abs}\,L_{abs} + K_{PV}L_{PV}}}$ (9)

whereK_{abs} is the absorber thermal conductivity, L_{abs} is the PV/T collector thickness, $K_{PV}$the Photovoltaic thermal conductivity and L_{PV} is the PV/T collector thickness.

From these equations, it is then possible to calculate the useful heat gain by the PV/T solar collector.

By rearranging equation (2), the thermal efficiency of the collector is given as:

$$\eta_t = F_R\,(\tau\alpha)_{PV} - F_R + U_L\frac{T_i - T_a}{G_T} \qquad (10)$$

Tiwari et al. (2006) gives the temperature dependent electrical efficiency(η_e) of a PV module as shown in equation 11.

$$\eta_e = \eta_r[1 - \beta(T_C - T_r)] \quad (11)$$

where$T_r$is the reference temperature,β is the Temperature coefficient, T_C is the temperature of the solar cells and η_r is the reference efficiency of PV module.

III. EXPERIMENT

A. *Determining the electrical and thermal energy demand from the system*

One of the major requirements of a PV/T system is to meet the expected demand of heat and electrical energy. Thus, before modelling and simulation, it was crucial to fix the expected demand from the PV/T as a system requirement. Consequently, both the electrical and thermal energy demand from the system was approximated. Tables 1and 2give a step by step approach used to approximate the expected demand from the PV/T system. The approximated demand capacities guided the modelling and simulation process in ensuring that the chosen model to be constructed meets the expected demand.

Using the expected electrical energy demand, the size (wattage) of the required solar panel was determined. Using the wattage determined, the solar panel was selected from arrange of solar panels available in the Kenyan market. The major factor used in settling in one of the panels is the aperture area exposed such that the one exposing the maximum area was chosen. The aperture area was important in ensuring maximum heat collection by the thermal absorber plate.

Table 1: Daily load energy demand for a typical Kenyan family of five

	Number of appliances	Power rating (W)	Voltage (V)	Average hours of usage/day	Daily Energy use (Wh)
Pump	1	50	12	5	250
Lighting bulbs	5	5	12	3	75
Television (Based on Sony 24" 22BX310 Widescreen LCD TV)	1	50	110~240	3	150
Cell phone recharging	5	2	100~240	2	20
Total daily system energy demand					**495**
Adjustment for losses (Inefficiencies in cables, modules, batteries, charge controllers and inverters)	10 % of subtotal				49.5
	Total daily system energy demand + losses				**544.5**

To determine the solar panel size (wattage) the operation system voltage was selected as 12V. Using the system voltage selected and the daily load energy demand from table 1, the daily system charge requirement was calculated.

$$\text{Daily system charge requirement} = \frac{\text{Total daily system energy demand + Losses(Wh)}}{\text{System voltage (V)}}$$

$$= \frac{544.5\text{Wh}}{12\text{V}} = 43.375\text{Ah}$$

43.375Ah is the charge in amp-hours that the module has to produce each day to meet the load requirements.

To determine the system design charging current, one must know the insolation value of the physical environment in which the PV/T system is to operate. For this study, the solar insolation value for a site near the University of Nairobi is given as 5.5 Peak Sun Hours(PSH) from the data outlined in appendix D (Hill, 2011). Thus, the system design charging current was calculated.

$$\text{system design charging current} = \frac{\text{Daily system charge requirement}}{\text{Design solar insolation value}}$$

$$= \frac{43.375\text{Ah}}{5.5\text{PSH}} = 8.25\text{A}$$

8.25A is the charging current the module should produce under normal operating conditions.

Alternatively, the required module can be determined by calculating the require module input in terms of wattage.

$$\text{Required solar panel input} = \frac{\text{Total daily system energy demand + Losses (Wh)}}{\text{Design solar insolation value}}$$

$$= \frac{544.5\text{Wh}}{5.5\text{PSH}} = 99\text{W}$$

From the required solar panel input, a solar panel that will generate 99watts per hour is needed.

A **100W** polycrystalline solar panel of TianweiYingli New Energy Resources Company, YLP100P-17b was chosen for the system. Other parameters for the chosen panel are listed below:

- Power 100W;
- Rated voltage 18.5V;
- Rated current is 5.41A;
- open circuit voltage is 22.9V;
- Short circuit current is 5.74A
- Maximum system Voltage is 600V.

Table 2: Estimates of hot water energy demand for a typical Kenyan family of five

	Typical Kenyan family water consumption		
	Average litres per use	Frequency per day	Litres per day
Showers	10	5	50
Dish wash	20	3	60
Food preparation	10	3	30
Total			**140**

From table 2, the Volumetric daily water demand, V= 140 L = $0.14m^3$/day.

Using the volumetric daily water demand, the hot water energy demand (D) for the family of five can be determined. Assuming cold mains water supply temperature (T_i) of 20^0C and water distribution temperature (T_o) of 45^0C, the hot water energy demand is determined as;

$$D = V\rho C_p(T_o - T_i)$$

where ρ is water density and C_p is the specific heat capacity of water.

Therefore, D = 0.14*1000*4.18*(45 - 20)
= 14630KJ/day
= 14.63 MJ/day

The thermal collector, whose area has been fixed by the PV module chosen, has to produce**14.63 MJ**of energy per day in order to meet the expected demand. Thus, to determine whether it is possible to generate this thermal load required, detailed simulation which took into account the available solar radiation and other parameters and performance characteristics of the collector components was conducted on a model developed in a transient system simulation tool (TRNSYS).

To simulate the PV/T system in TRNSYS, an hourly consumption profile is required. Though the hot water demand is never uniform and is subject to daily variations, the consumption profile gives a repetitive load for the sake of making practical sense. Figure1 gives an assumed consumption load for the 140L of the hot water demanded by the design family of five within 24 hours.

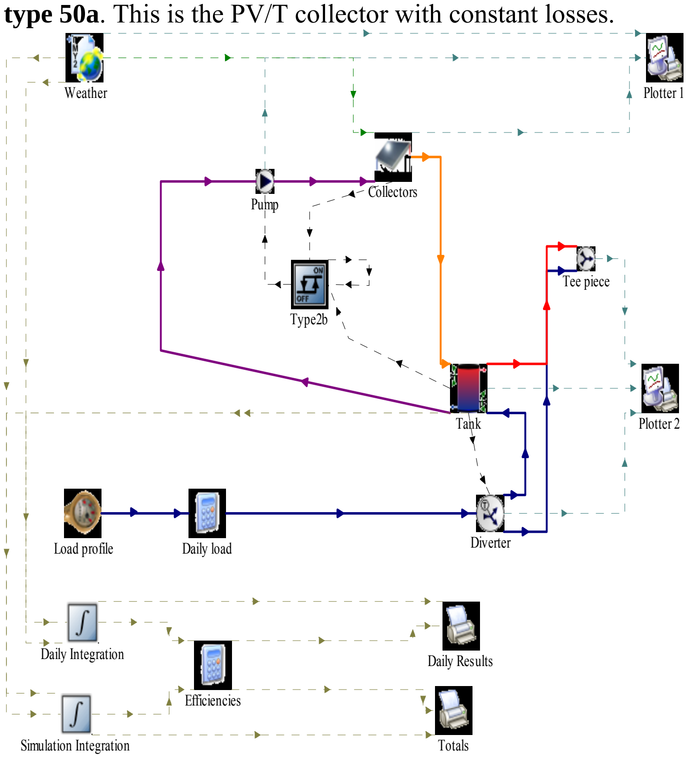
IV. MODELLING APPROACH

A model of the PV/T system was developed in the commercial modelling and simulation software TRNSYS. This is a graphically based software environment used to simulate the behaviour of transient systems. The program consists of many subroutines that model subsystem components. Since all the components of the system had been identified and a mathematical description of each component was available, an information flow diagram for the system was constructed. The purpose of the information flow diagram was to facilitate the identification of the components and the flow of information between them. From the flow diagram, a deck file was constructed containing information on all system components, weather data file and the output format.

The system is modelled with the TRNSYS software and a typical meteorological year (TMY) conditions for Nairobi, Kenya. TMY is defined as a year, which sums up all the climatic information characterizing a period as long as the mean life of the system. The mathematical models for the subsystem components are given in terms of their ordinary differential or algebraic equations. The program has the flexibility of interconnecting components in any desired manner thus to simulate a system one has to identify all the components of the system and formulate a general mathematical description of each.

Each component is represented as a box which requires a number of constant PARAMETERS and time dependent INPUTS and produces a time dependent OUTPUTS. An information flow diagram shows the manner in which all system components are interconnected. A given OUTPUT may be used as an INPUT to any number of other components. A simplified information flow diagram for the hybrid PV/T solar system under investigation is shown in figure 1.

The main component of the TRNSYS deck file constructed is **type 50a**. This is the PV/T collector with constant losses.



V. Figure 1: Information flow diagram for the model constructed in TRNSYS

V. RESULTS AND DISCUSSION

The simulation results include the overall efficiency of the system, the total amount of energy collected from the system and the water temperatures from the system. The results were randomly chosen to plot graphs to correlate various parameters of the PV/T system.

VI. OPTIMIZATION OF THE WATER FLOW RATE

The rate at which water flows through the PV/T collector tubes determines how much heat energy can be collected from the PV panel. Therefore, there is a need to determine an optimum flow rate, which maximizes both the electrical and thermal energy collected. This design flow rate is very crucial in ensuring maximum overall efficiency of the PV/T system designed.

To determine the optimum flow rate, the annual energy output of the TRNSYS model was determined for various flow rates. The annual output of both electrical and thermal energy for various flow rates is shown in table 3.

Table 3: Annual output of electrical and thermal energy for various water flow rates

Water flow rate (L/h)	Electrical Energy output (GJ)	Thermal Energy output (GJ)	Total energy output (GJ)
0	1.332	0	1.332
15	1.568	2.567	4.135
25	2.544	5.678	8.222
50	2.683	3.432	6.115
100	2.765	1.678	4.443
150	2.781	0	2.781

The optimum flow was determined by plotting the water flow rate against the total system output energy versus as shown in figure 2. The optimum flow rate corresponds to 25L/h. This is the flow rate value, which maximizes the energy collected from the system. The total system energy collected increases rapidly and peaks at a flow rate of 25L/h before decreasing. The decrease in total system energy collected after attaining a flow rate of 25L/h is approximately linear.

It was noted that the thermal energy collected increases steadily with increase in flow rate and peaks at 25L/h and drops subsequently. Even though the electrical energy collected increases steadily with increased flow rate, it is vital to note that the value increases dismally after a flow rate of 25L/h is attained. The increase in electrical energy production can be attributed to the panel working at low temperatures.

Figure 2: Graph of water flow rate through the PV/T collector as a function of total system output (TRNSYS model)

VII. HOURLY PERFORMANCE OF THE SYSTEM

The results obtained were used to illustrate the performance of the PV/T model. Figure 3shows performance of the system on an hourly basis in terms of thermal and electrical output. The optimum flow rate of 25L/h was used.

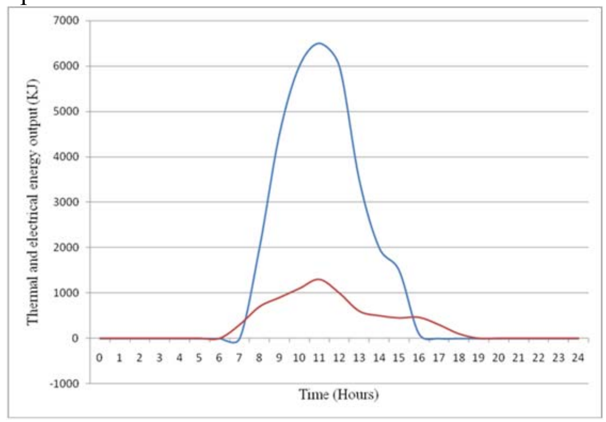


Figure 3: Electrical and thermal energy output from the TRNSYS Model in a period of 24 hours

Figure 4 shows the performance of the system on 27thAugust in relation to the solar radiation. It was observed that the energy collected is directly proportional to the solar radiation since the total energy collected curve and the solar radiation curve have a similar pattern.

Figure 5 shows the performance of the system on 27th August in relation to the time of the day. A total efficiency of about 48% is achieved at around 10am. A combined maximum efficiency of about 48% is achieved between 10 – 12 am. In case of a non-hybrid system (PV alone), this corresponds to 6% electrical efficiency. Thus, incorporating a heat collection system has greatly influenced the conversion rate of incoming solar radiation as witnessed from the enhanced efficiency.

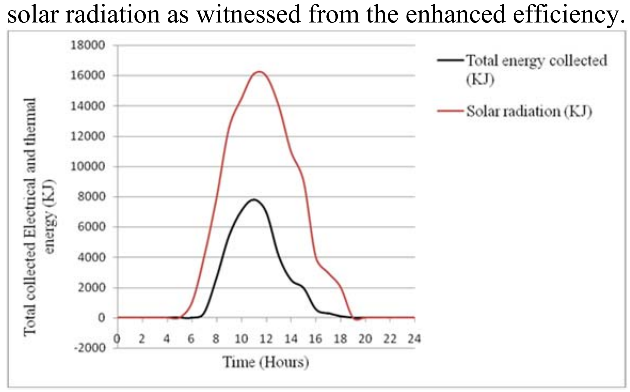


Figure 4: The hourly total heat and electrical energy collected versus Total solar radiation

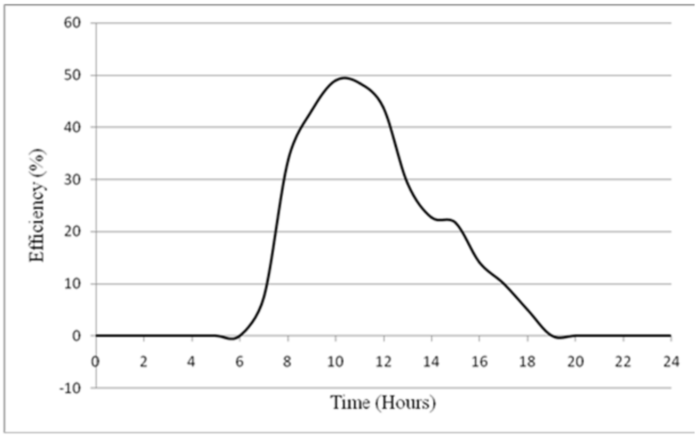


Figure 5: The hourly efficiency of the model

VIII. THERMAL PERFORMANCE

Figures 6 and 7 present the panel thermal behaviour when water is flowing through the PV/T collector to effect cooling and when there is no water flowing through the collector respectively. The maximum solar intensity for both cases occurs at around 12 noon. This indicates that the local solar noon for a site within the University of Nairobi is around 12 noon. There is a drastic dip in both solar intensity and average panel temperature at around 1 pm. This is due to cloud cover which lasted for about 30 min.

For the case with cooling, the maximum attained panel temperature is 77.5^{o}C whereas for the case with no cooling the maximum is 83^{0}C. Whereas the case with cooling the average panel temperature varies between 39 and 77.5, the temperature for the case with no cooling remains almost constant at a value above 70^{0}C (figure 8). The temperature profile of the PV/T corresponds to the intensity as observed in figures 6 and 7; provide vital information on the importance of cooling and give an indication of how much heat energy can be collected from the PV panel by the cooling fluid.

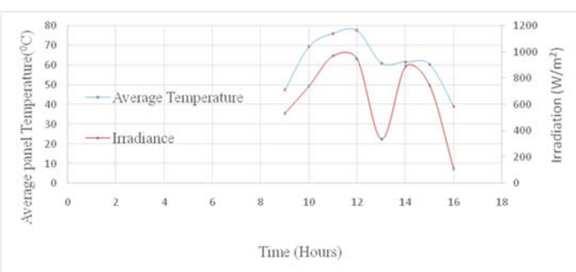


Fig.6 Irradiance versus Average panel temperature for the whole day

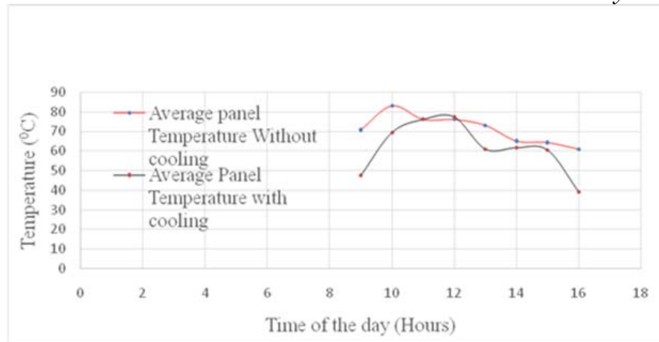


Fig.7: Panel temperature profile when water is flowing through the PV/T

IX. ELECTRICAL PERFORMANCE

Electrical efficiency(η_e) is given as:

$$\eta_e = \frac{V_{mpp} I_{mpp}}{G A_c} \quad (12)$$

From figure 8 it can be noted that the electrical efficiency range is between 8 and 10%. Temperature differences are a major factor that affects the efficiency of the solar panel. It can be concluded that the efficiency values do not fluctuate with very big ranges owing to the stabilized temperature of the panel.

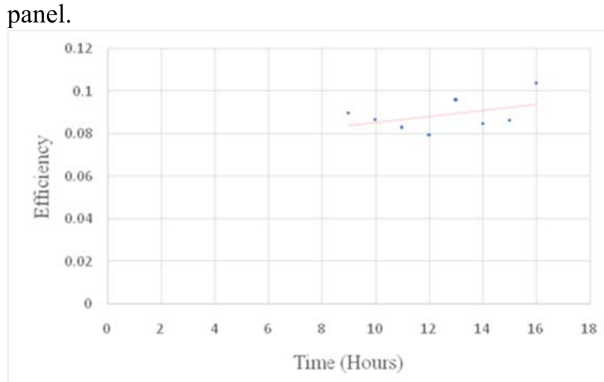


Fig. 8 Electrical efficiency against time of the day

The concept of total system efficiency$\eta_o$is used to evaluate the overall system performance and is given by:

$$\eta_o = \eta_t + \eta_e \quad (13)$$

The overall efficiency of the PV/T panel on 27th August 2014 is shown in table 7. It can be noted that electrical efficiency of the PV/T panel is stable compared to the thermal efficiency which fluctuates significantly. This can be attributed to the fact that thermal efficiency is not only a factor of solar radiation but also other factors such as ambient temperature, heat loss to the surroundings, and other meteorological parameters (Chow, 2010). The total efficiency of the system is between 37 to 62%. This proofs that the overall efficiency of the PV/T system is much higher than that of a separate PV system which ranges up to 10% in practical applications (figure 8). This implies that the PV/T system can harness solar energy more adequately as compared to a stand-alone PV system.

Table 7: Table showing the PV/T panel efficiencies

Time of the day (Hours)	Thermal efficiency of the PV/T panel (η_t)	Electrical efficiency of the PV/T panel (η_e)	Overall Efficiency of the PV/T Panel ($\eta(\eta_e)$
0900	0.523	0.090	0.613
1000	0.377	0.089	0.466
1100	0.287	0.083	0.370
1200	0.302	0.080	0.382
1300	0.835	0.096	0.931
1400	0.318	0.085	0.403
1500	0.383	0.086	0.469

X. CONCLUSIONS

The conclusions from this paper can be summarized as below:

i. The optimum water flow rate through the PV/T was determined as 25L/hour.
ii. The combined efficiency of the PV/T system is determined to range between 37 and 62% impractical applications which are way higher than any PV system.
iii. The lifecycle savings of the system are Kshs. 85941 and the payback period is determined as 5.2 years; both figures are quite promising.
iv. The system could meet up to 47% of the total heat energy demand for a Kenyan family of five.

The low value of the optimum flow rate determined from simulation is an indication that the PV/T system could be implemented in thermo-syphon mode. This would greatly influence the cost of the overall project since it would eliminate the use of the DC pump which accounts for nearly half of the investment costs. This would further enhance the economic viability of the system since it would reduce the investment costs and the payback period.

Although a specific application was studied in this work, I strongly believe that PV/T systems can be utilized in a variety of applications requiring both electricity and low temperature hot water. The systems would be even more applicable and economic friendly as the cost of solar panels consistently decrease. This is further aided by the fact that solar equipment are zero rated in regard to tax deductions.

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