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Design of concentrated photovoltaic (CPV) system for a small campus in Mansoura-Egypt

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Abstract: *The concentrated photovoltaic (CPV/T) module is a solar collector that consists of both solar thermal collector and photovoltaic (PV) module. So, it produces electric and heat energy simultaneously. This paper presented a design for CPV/T model for supplying a small campus in Mansoura- Egypt. The campus needs both electric energy and hot water for its operation, so using CPV/T module is the best choice. The proposed model is based on modelling the conventional PV. Then determine the irradiation concentration ratio which depending on the type of optical material. Finally, a water-cooled concentrated PV is modeled and designed. Moreover, the equations for determining the electric and thermal generated from the CPV are presented. The simulation results prove that, the electrical output power and the efficiency of the CPV are increased due to using the water cooling which reduces the temperature of the CPV system under 50^{o}C. In addition, high water flow rate can directly extract thermal heat through the CPV/T module. This obviously enhances the thermal efficiency of CPV/T system.*

Keywords: Photovoltaic (CPV), Water cooling, PV electrical and thermal efficiency, Cogeneration efficiency.

I. INTRODUCTION

Solar energy is the basis of almost all renewable energy on earth. Solar technologies and devices use the sunlight to provide lighting, heating, electricity, etc. for residential and some industrial applications. PV is considered one of the technologies that utilize the solar energy. It converts the sunlight directly to electrical energy. However, most of the solar radiation reaches the solar cells are converted to heat energy and thus increase the cell temperature causing a reduction in electric efficiency. Photovoltaic systems convert sunlight to electric energy, by either flat-plates PV or concentrated PV (CPV) modules [1].

CPV systems are based on using an advanced optical material to concentrate the sunlight on each PV cell for obtaining maximum efficiency. Also, it uses the focused sunlight to reduce the cost of generated solar energy. It can be operated at higher temperatures than conventional photovoltaic modules. Therefore, due to temperature increase, most of the solar energy absorbed are converted to thermal energy. So, Photovoltaic thermal solar (PV/T) modules describe the collectors that produce both electric and useful heat energy from solar cells. Increasing of cell temperature causes a decrease in PV electrical efficiency. Adding cooler to the PV system improves the electrical and overall efficiency.

Different technologies were used for cooling the CPV modules. These technologies such as; Floating Tracking Concentrating Cooling (FTCC) or water spray [2-3], forced air circulation [4-13], Phase-Change Materials (PCM) [14-16], transparent coating (photonic crystal cooling) [17-18] and forced water circulation [19-27].

The FTCC uses a sprinkler to spray water on the surface area of the CPV. Ref. [2] presented a method to improve the luminescent solar concentrators efficiency by using a thin film of Poly Methyl Methacrylate (PMMA). There was an increase in optical efficiency of about 10–14% greater than the luminescent solar concentrators. A theoretical model of solar dish concentrator was developed in [3] to predict the temperature of the CPV module. The results were compared with an experimental data. In FTCC method the sprinklers cannot coverall CPV surface area. This means that, some parts will not be cooled. Also, this method does not utilize the hot water.

The CPV air cooling system is used to improve the maximum heat gain of PV surface by using controlled air flow. The CPV air type collector is effective, and simple in operating and design. Sopian et al. [4] and Hagazy [5] developed a thermal model to a glazed CPV air cooling system for using it in space heating and drying purposes. Coventry [6] investigated the efficiency of the CPV module to improve the overall electrical and thermal efficiency of CPV system to 11% and 58%, respectively. Tiwari at al. [7] used an air duct to improve the performance of the PV module. The results proved that there was an improve in overall efficiency. Refs. [8-9] determined the performance of the different schemes of PV/T air module. The results showed that the glass to glass PV with air duct gave the best efficiency among all the studied cases. The efficiency varied in between 9.75% and 10.41% for the four considered cases. Experimental analysis of PV air cooling was discussed in [10]. The results illustrated that, the PV temperature was decreased by 2-3°C with air cooling whereas the maximum output power was increased by 6-14% after using air cooling. An experimental analysis of a PV/T air collector was performed in [11]. It showed that the electrical and thermal efficiencies of PV/T module were about 15% and 22%, respectively. Ref. [12] developed an air-cooling type collector to improve the electric energy of CPV module by moving air. Ref. [13] applied Extreme Learning Machine (ELM) technique in air type CPV system to estimate its performance. The main drawback of the forced air-cooling system lies in thermal energy waste.

Phase-Change Material (PCM) technology reduces the CPV surface temperature. It stores the thermal energy from the CP/V module in the melting process of the PCM. It can store great amounts of thermal energy with small value of temperature differences. Ref. [14] investigated the electrical efficiency of the PV/T module by using pure and combined PCM. This method improved the electrical efficiency by an average of 5.8%. Hasan et al. [15] developed a model to predict the melting and solidification fractions of the PCM, and applying that model to increase both the electrical energy (by 5.9%) and the cost-effectiveness. Ref. [16] designed a novel concentrated photovoltaic thermal hybrid solar (PV/T), collector. It involved two absorber plates painted by two selective surfaces (paints). The results illustrated that, the thermal energy of the designed PV/T was increased more than 60% and the total efficiency of the PV/T was 80%. The phase-change material technique has less efficiency in colder regions and there is a reduction in material absorption ability over the time.

Transparent coating is a thin layer material on top of the solar cell. It allows solar wavelengths to pass through the cell and prevent thermal wavelengths. So, it eliminates the temperature increase and improves the PV module efficiency [17]. The Micro-photonic design was applied to cool the PV module through a cooling radiator [17]. A modified three-dimensional metallic photonic crystal was used to match emission spectrum for the useful thermo-photovoltaic [18]. In this method, the temperature problem was eliminated, which investigates the CPV module efficiency. However, there is a great wasted in thermal energy.

Forced water cooling system technology increases both the thermal and electrical efficiencies. It provides a hot water for domestic applications. The water-cooled CPV module performance was analysed experimentally in [19]. The efficiency was increased and hence more electric power output was produced. The electric output power of the CPV was 4.7 to 5.2 higher than the conventional PV cell. Ref. [20] presented an experimental and mathematical model for the PV heat pump to calculate the electrical efficiency and power generation of the PV modules. Ref. [21] presented an experimental performance analysis for CPV with water cooling system. The results indicated that the CPV module temperature was decreased to 60°C using cooling water and therefore the performance of the CPV has improved.

Ref. [22] designed and fabricated an air- and water-cooling system for the PV module to maintain the operating temperature at constant value. The dropped temperature increased the efficiency of the solar cells from 9% to 14%. Ref. [23] offered an experimental analysis of PVT systems consisted of PV modules and water heat extractor. Ref. [24] proposed a numerical model to analyze the hybrid PVT performance. It investigated the impact of the mass flow rate of the water on the thermal and electrical and efficiencies. Ref. [25] presented hybrid photovoltaic thermal solar collectors. The thermal efficiency of the hybrid PVT system was between 45% and 70%. The nature convection PV thermosyphon water heating system was used with aluminum-alloy flat box to increase the electrical and thermal efficiencies [26-27].

This paper presents a mathematical model of CPV/T system with water cooling. Both the electric and thermal energy and their efficiencies are investigated in that model. The impact of irradiance concentration ratio on both electric and thermal efficiencies are also explored in the paper. The presented model is simulated using Matlab program. Finally, the design steps of CPV system to supply a domestic load in Mansoura – Egypt with electric and thermal energy are presented.

II. Mathematical Model of CPV/T System

The thermal concentrated PV system generates thermal and electrical energy. Each type of generated energy is calculated by separate equations (Annual and daily).

2.1 Solar radiation model

The total solar irradiation incident on the horizontal surface is determined from the following relation:

$$G = G_B + G_d \tag{1}$$

The beam irradiation falls on a horizontal surface is expressed by;

$$G_B = G_{Bn}\sin(\alpha) \tag{2}$$

$$G_{Bn} = A\,exp\left(\frac{-B}{\sin(\alpha)}\right) \tag{3}$$

The solar altitude angle (α) is calculated from the following relation [28]:

$$\sin(\alpha) = sin\,\delta\sin L + cos\delta\cos L\cos h \tag{4}$$

$$h = \pm\frac{1}{4}\,(number\;of min\;from\;local\;solar\;noon) \tag{5}$$

$$\delta = 23.45\,sin\left[\frac{360}{365}(284+n)\right] \tag{6}$$

Where n is the day number, such that $n = 1$ on the 1st January and 365 on December 31st.

The diffuse solar irradiation G_d in Eq. (1) can be calculated by:

$$G_d = C_d G_{Bn} F_{ss} \tag{7}$$

The angle factor between the sky and the surface can be calculated from the following equation:

$$F_{ss} = \frac{1}{2}(1+\cos(s)) \tag{8}$$

2.2 PV Model

The PV cell temperature can be expressed as a function of irradiation and its concentration ratio as follows [29]:

$$T_C = T_{amp} + \left(\frac{NOCT - 20^oC}{800}\right) C * G \tag{9}$$

The concentration ratio, *C*, solar irradiance, *G*, and the cell temperature affected the short circuit current of the PV, I_{sc}, as follows [29]:

$$I_{sc} = I_{SCref}\frac{(1+k_i\Delta T)\,CG}{G_{ref}} \tag{10}$$

The open circuit voltage of the PV is affected by the cell temperature as follows [16]:

$$V_{OC} = V_{oc,ref}(1 + k_v\Delta T) \tag{11}$$

The diode saturation current I_o varies with temperature and can be expressed as follows.

$$I_O = \frac{I_{sc}}{\exp\left(\frac{V_{oc}}{aV_T}\right)-1} \tag{12}$$

where V_T is the terminal voltage, equal to 0.0258 at the room temperature and a is the ideality factor of diode (1 and 1.5). The relation between PV voltage and current influenced by the temperature is calculated by;

$$I = I_{sc} - I_O\left[\exp\left(\frac{V}{aV_T}\right) - 1\right] \tag{13}$$

Also, the relation between the PV voltage and power influenced by the temperature is calculated by;

$$P_e = I \times V = I_{sc} \times V - I_O \times V\left[\exp\left(\frac{V}{aV_T}\right) - 1\right] \quad (14)$$

The PV efficiency is determined as a function of cell temperature [30]:

$$\eta_{pv} = 0.15[1 - 0.0045(T_c - 25)] \quad (15)$$

2.3 CPV efficiency model

The ideal thermal power absorbed by PV module can be obtained by [31]:

$$Q_{th,a} = \{(1 - \eta_{pv}).\eta_{opt}.C.G. - [\bar{h}_C.(T_C - T_{amb}) + \varepsilon_C.\sigma.(T_C^4 - T_{amb}^4)]\}.A_C.N_m \quad (16)$$

where η_{opt} is the total optical efficiency, $\eta_{opt} = 85 - 95\%$, and $\bar{h}_C$ equal to 10-25 W/m^2. K.

In particular, the relation that regulates the heat exchange between the cell and the absorb plate, is defined as:

$$T_p = T_C - \left[\dot{Q}_{th,a}.\left(\frac{t}{N_m.A_C.k}\right)\right] \quad (17)$$

The variation of the thermal energy output relative to the temperature of the input fluid, T_{in}, mass flow rate of fluid $\dot{m}$ and outlet fluid temperature T_{out} is given by the equation below:

$$\dot{Q}_{th,a} = \left[\dot{m}.C_p.(T_{out} - T_{in}) = h_c A_c \frac{T_{out} - T_{in}}{\ln\left(\frac{T_p - T_{in}}{T_p - T_{out}}\right)}\right] \quad (18)$$

The convective heat transfer coefficient of fluid h_c for laminar and turbulent flow can be estimated from the following relations:

$$Nu = \frac{h_c L_c}{k_l} = \begin{cases} 0.664\, Re^{\frac{1}{2}}\, Pr^{\frac{1}{3}} & , Re \le 5 \times 10^5 \\ 0.023\, Re^{4/5} Pr^{2/5}, & Re > 5 \times 10^5 \end{cases} \quad (19)$$

Where N_u and R_e are the Nusselt and Reynolds number respectively, $R_e = \frac{\rho u L_c}{\mu}$, L_c is the characteristics length and P_r is the Prandtl number.

The electric efficiency is evaluated from the following equation:

$$\eta_e = \frac{I.V}{GA_c} \quad (20)$$

Thermal efficiency can be calculated by;

$$\eta_{th} = \frac{Q_{th,a}}{G\,A_c} \quad (21)$$

The cogeneration efficiency of the CPV/T system is the sum of the two efficiencies:

$$\eta_{cog} = \frac{P_e + Q_{tha}}{GA_c} = \eta_e + \eta_{th} \quad (22)$$

2.4 Sizing the solar CPV System

The required daily energy from the PV system can be calculated by;

$$E_{pv} = \frac{daily\ average\ energy\ consumption}{overall\ efficiency} = \frac{E_L}{\eta_{inv} \times \eta_{bat} \times \eta_{reg} \times \eta_{cab}} \quad (23)$$

where η_{inv}, η_{bat}, η_{reg}, η_{cab} and η_o are inverter efficiency, battery efficiency, regulator efficiency, cable efficiency and overall efficiency respectively. The peak power of solar PV can be calculated as following [32]:

$$P_{pv} = \frac{E_{pv}}{minimum\ peak\ sun{-}hours\ per\ day} = \frac{E_{pv}}{T_{min}} \quad (24)$$

The total required current can be calculated by:

$$I_{DC} = \frac{peak\ power\ of\ solar\ PV\ array}{System\ DC\ Voltage} = \frac{P_{pv}}{V_{DC}} \quad (25)$$

The number of parallel PV modules can be calculated by the following equation:

$$N_p = \frac{Total\ module\ current}{Rated\ curren\ to\ one\ module} = \frac{I_{DC}}{I_r} \quad (26)$$

The number of series PV modules can be calculated by the following equation.

$$N_s = \frac{System\ DC\ voltage}{Module\ rated\ voltage} = \frac{V_{DC}}{V_r} \quad (27)$$

The total number of modules, N_m, that equals to the multiplication of the series and parallel modules;

$$N_m = N_p \times N_s \quad (28)$$

III. DESIGN PROCEDURE OF PV/T SYSTEM

The CPV/T model is executed in MATLAB 2014b [33]. Figure 1 shows the flowchart of the design steps. After the entering of the input values, the solar radiation.n and PV models are run to calculate the required parameters.

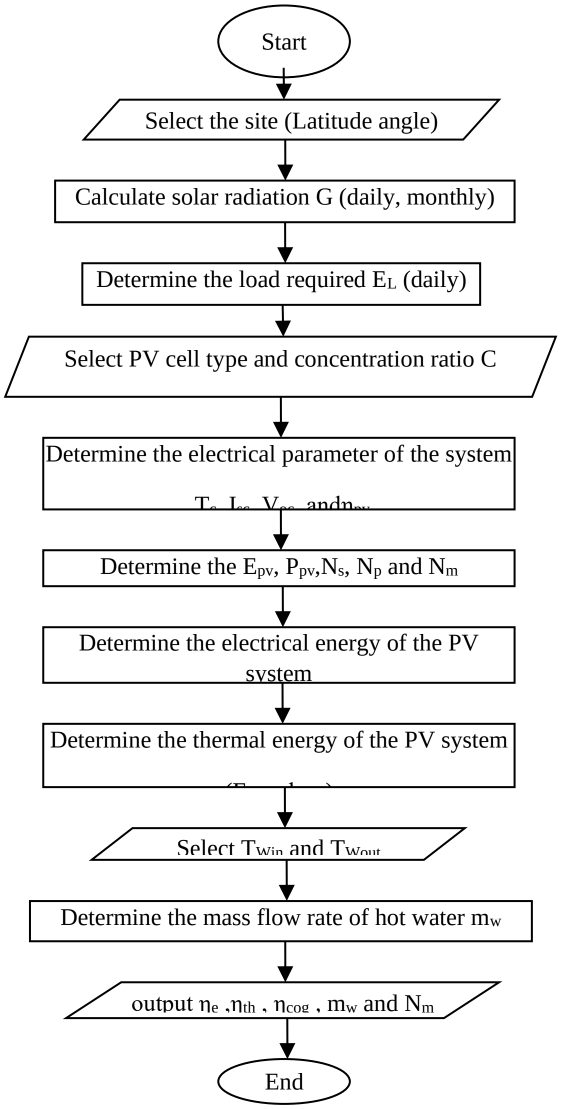

Fig. 1. flowchart of the design steps

IV. DATA DESCRIPTION

The proposed model of CPV/T is evaluated using daily solar irradiance G. This irradiance was calculated at a selected location Dawadmi (KSA, long. 44°23′38″E , latitude 24.50444°N). The calculations have been carried out each 1 h, from 8 h to 16 h and that during a day, Jan 7th. The hourly solar radiation on the test day (7th January) is expressed by Fig. 2 and the peak solar radiation at solar noon is 824 W/m^2.

The monthly average daily values of diffuse solar radiation data incident on horizontal surface and on tilted surface (s=30°) at the considered site, Dawadmi (KSA, long. 44°23′38″E, latitude 24.50444°N) are illustrated in Fig. 3.

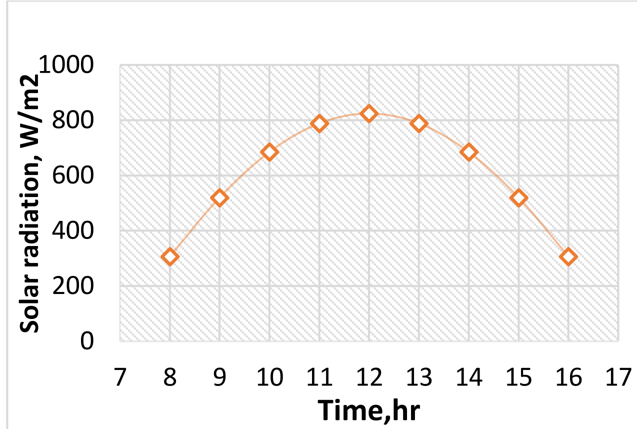

Fig. 2. Hourly solar radiation for (Dawadmi City, KSA) (7th January)

The solar energy incident in the selected location is very large especially during the summer months, where it exceeds to 8.3 kWh/m^2/day on horizontal surface. The annual average daily value of diffuse solar radiation on a horizontal surface for this area is 7.45 (kWh/m^2/day).

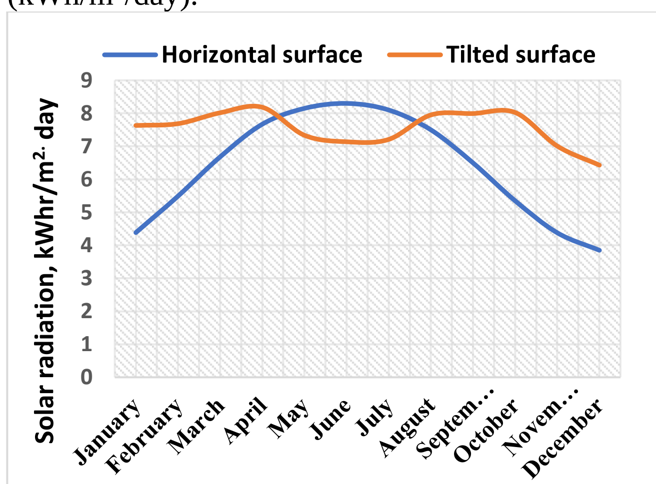

Fig. 3. Monthly average global radiation on the horizontal surface and on a 30° tilted plane

The daily load distribution is necessary for the PV system design process because the variation of the load during the day and night will affect the required number of PV panels, and hence the capacity of storage battery and inverter. There are different load values for different seasons, the load is taken as 340 kWh/day for the summer season, and 230 kWh/day for the winter. The power consumption varies according to the daily activities. For example; most of the power taken by the kitchen, rooms, offices, and the laundry are assumed to

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be during the day.

The hourly load demand of the site under study for the two seasons per hour during day and night is represented in Fig.4.

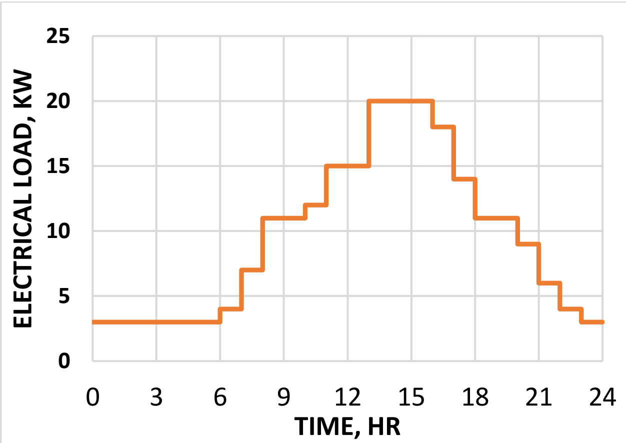

Fig. 4. The hourly electrical load of the small campus in winter season

V. RESULTS AND DISCUSIONS

The PV system design is the process of determining the appropriate ratings of the current and voltage for each electrical component of the PV system to meet the proposed electrical load. The select panel in this paper is a SPT250-20WC and the specification of PV panel is shown in Table I.

TABLE I
THE PV PANEL SPECIFICATIONS

Maximum power rating at STC (P_{max})	250 W
Current at P_{max} (I_{mp})	8.15 A
Voltage at P_{max} (V_{mp})	30.7 V
I_{sc}	8.63 A
V_{oc}	37.4 V
Dimensions	164 × 99 × 3.5 cm

The proposed algorithm was applied on the site and load data using the designed MATLAB program. The results of solar PV system sizing are summarized in Table II.

TABLE II.
SIZING OF SOLAR PV ARRAY

Model name	PV- SPT250-20WC
Maximum demand load	340 kWh
The daily energy requirement from the solar PV	495.7 kWh
Concentration ratio	2
Peak power of solar PV array	43 kW
Total number of modules, N_{pv}	176
Number of parallel modules, N_p	44
Number of series modules, N_s	4

The temperature of flat PV cell and the concentration PV with time are illustrated in Fig. 5. The temperature of flat PV and the concentration PV (C=2) reach to the maximum value at the noon time. As illustrated in Fig. 5, the maximum temperature difference between them was lower than 27.8°C.

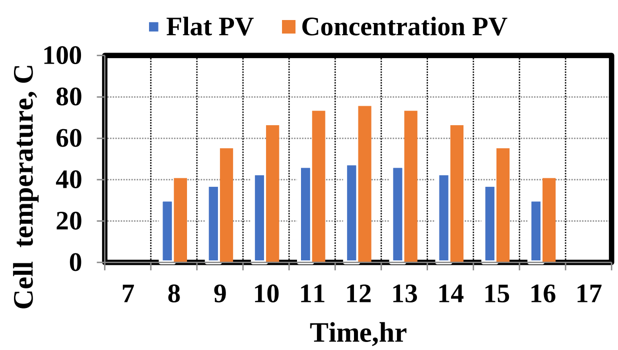

Fig. 5. flat PV and CPV temperature during a day

The electrical efficiency of the flat PV and the CPV using cooling water during the day (7th January) at C=2 are shown in Fig.6. The average efficiency of the flat PV and the CPV using cooling water are 10.18% and 13.2%, respectively as shown by Fig. 6. Also, the PV performance with a concentration ratio and cooling is higher than the flat PV at the same input conditions.

Figs. 7 and 8 show the water flow rate effect on the average thermal and electrical efficiency of the CPV/T system during the day (February 21th) at C=2 and solar radiation G=800 W/m^2.

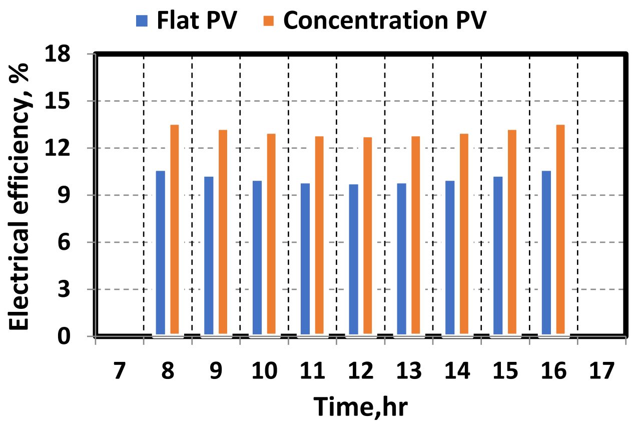

Fig. 6. Electrical efficiency of CPV and flat PV with respect to day time

As can be seen, increasing the water mass flow rate from 1 to 10 kg/s results in the increment in the average electrical efficiency from 12.92 to 13.73 % and the average thermal efficiency increases from 34.84 to 54.43%. The output electrical energy and thermal energy from the CPV/T system increase as the flow rate increases.

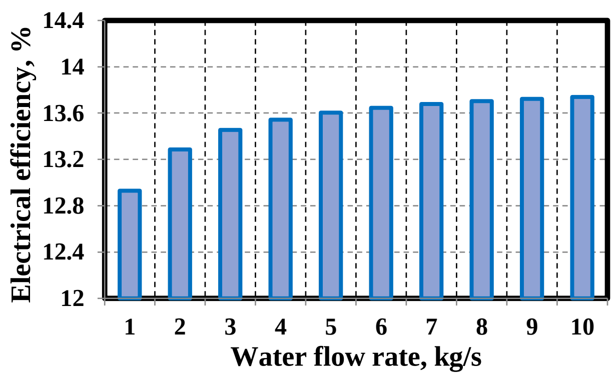

Fig.7 Electrical efficiency versus water mass flow rate at G=800 W/m^2 and C=2

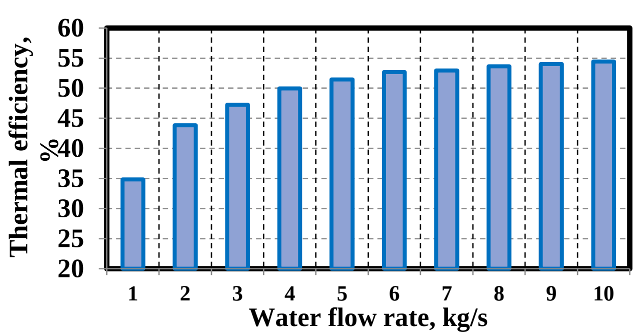

Fig. 8 Thermal efficiency versus water mass flow rate at G=800 W/m^2 and C=2

The electrical and thermal efficiencies of the CPV/T with time are illustrated in Fig. 9. It is obvious that, the electrical efficiency of CPV has the lower value at solar noon and the thermal efficiency has the higher value due to the higher cell temperature. In CPV/T, as the solar radiation increases, the cell temperature also has increased. Therefore, more heat will be extracted from the CPV module by the cooling water. Also, it is observed that the average electrical, thermal and cogeneration efficiencies of CPV/T are 13.2%, 43.75%, and 56.95 %, respectively.

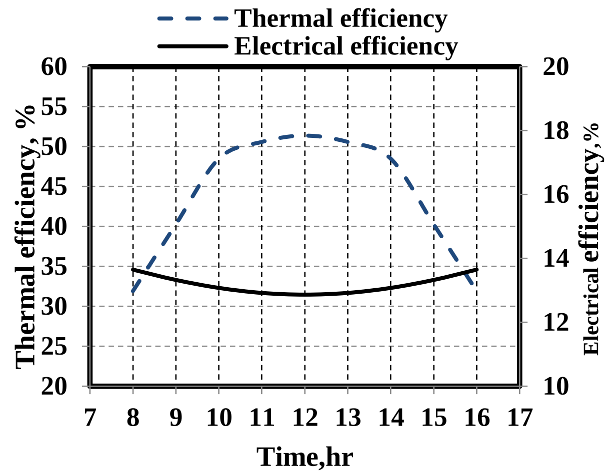

Fig. 9. CPV/T electrical and thermal efficiencies at C=2

The thermal, electrical and cogeneration efficiencies of the concentration solar cell (C=2) at hot water outlet 50 °C are shown in Fig. 10. As explained in the figure, the maximum thermal, electrical and cogeneration efficiencies are about 59.97%, 13.11 %, and 72.1 %, respectively. The annual average of the thermal, electrical and cogeneration efficiencies are about 48.18 % in, 12.34 %, and 60.52 %, respectively.

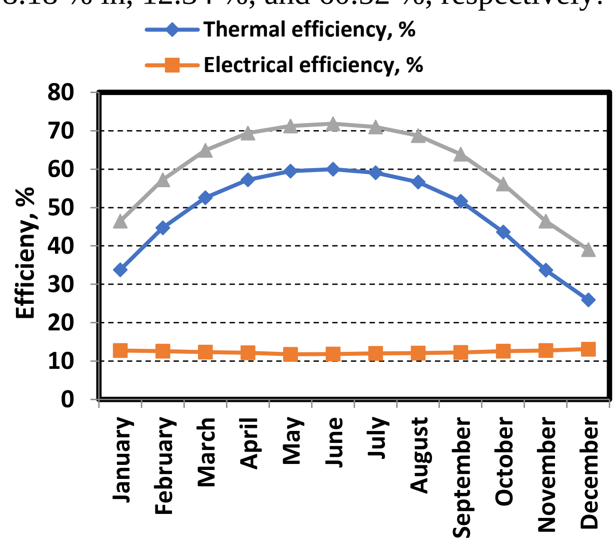

Fig. 10. The thermal, electrical and cogeneration efficiencies of the concentration solar cell at C=2 and T_{out}= 50° C.

VI. Conclusions

In this work, theoretical analysis of a CPV/T module performance with cooling water was presented. It is concluded that:

1- A CPV/T system fed electric power and hot water to a small campus in a Mansoura–Egypt was presented.
2- A mathematical model of CPV/T collector was used to carry out multi parameters analysis and to predict quite well the thermal, electrical and cogeneration efficiencies of a CPV/T collector.
3- The results proved that the solar PV cell performance with concentration ratio and cooling was much better than the flat PV at the same conditions.
4- With the cooling effect of water flow rate on CPV/T system, the PV efficiency was improved. In addition, high water flow rate directly extracted thermal heat through the CPVT array. This obviously enhanced the thermal efficiency of the CPV/T system. The average cogeneration efficiency of the CPV/T system reached up to 60.52 %.
5- The electrical and thermal energy outputs of CPV/T system was increased by increasing the water mass flow rate.

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