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Modeling of water cooled concentrated photovoltaic (CPV) system fed a small campus in Mansoura University – Egypt

نمذجة نظام خلايا ضوئية مركزة مبردة بالماء لتغذيةمدينة جامعية صغيرة بجامعة المنصورة

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

مجمع الخلايا الضوئية (الخلايا الفوتوفولتية) المركزة والحرارية يعتبر مجمع شمسى يجمع بين نموذج الخلايا الضوئية والمجمع الحرارى الشمسى وذلك لانتاج الطاقة الكهربية والطاقة الحرارية معا. يقدم هذا البحث نمذجة ومحاكاة لخلايا ضوئية مركزة ومجمع حرارى يغذى مدينة جامعية صغيرة داخل جامعة المنصورة بمصر بإستخدام برنامج الماتلاب. تحتاج المدينة الجامعية إلى طاقة كهربية ومياه ساخنة للإستخدام لذا يتطلب لهذا الغرض إستخدام مجمع الخلايا الضوئية والمجمع الحرارى. الحمل التقديرى للمدينة يقدر بحولى 340 كيلووات.ساعة/يوم في فصل الصيف و 230 كيلوات.ساعة/يوم فى فصل الشتاء. ويتم حساب كلا من الطاقه الكهربية والحرارية وكفاءتهما فى النموذج المصمم. وكما تم ايضا حساب تاثير زيادة نسبة تركيز شدة الاشعة عليها. وتشير النتائج التى توصلت إليها الدراسة إلى أن درجة الحرارة لنظام الخلايا الضوئية المركزة مع وجود مياه إنخفضت لأقل من 50 درجة سليزيس وبالتالى الكفاءة والقدرة الكهربائية زادت. بالإضافة إلى أنه عند معدلات سريان عالية للمياه يؤدى ذلك إلى إستخلاص طاقة حرارية مباشرة من خلال منظومة الخلايا الضوئية المركزة. وهذا يؤدى إلى تحسين الكفاءة لنظام الخلايا الضوئية المركزة والحرارية. ووجد أيضاً أن متوسط الكفاءة الكلية لنظام الخلايا الضوئية والحرارية وصل إلى 60.52%

***Abstract*—A concentrated photovoltaic-thermal (CPV/T) collector is a solar collector that combines a photovoltaic (PV) module with a solar thermal collector and produces electricity and heat simultaneously. This paper presents the modeling and simulation of CPV/T collector model fed a small campus in Mansoura university- Egypt (31° 04′N, 31° 21 ′ E) using MATLAB code. The campus needs the electricity and hot water for operation, so using CPV/T collector is a promising idea. The estimated load for different seasons is taken as 340 kWh/day for the summer season and 230 kWh/day for the winter. The electric and thermal energy and their efficiencies are calculated in the designed model. Also, the impact of the irradiation concentration ratio on both electric and thermal efficiencies are investigated. The simulation results show that the temperature of the CPV system using water cooling is reduced under 50ºC and therefore the electrical efficiency and electrical power output of the CPV are increased. In addition, high water flow rate can directly extract thermal heat through the CPV/T array. This obviously enhances the thermal efficiency of CPV/T system. The average cogeneration efficiency of the CPV/T system reaches up to 60.52%.**

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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. Solar photovoltaic (PV) is one of the technologies to utilize solar energy to convert sunlight directly into electrical energy. However, most of the solar radiation reaches the solar cells are converted to heat energy and thus increase the temperature causing a reduction in electric efficiency. Photovoltaic systems convert sunlight to electric energy, by either flat-plate photovoltaic (PV) or concentrating photovoltaic (CPV) modules [1].

Concentrating photovoltaic (CPV) systems depend on an advanced optical system to focus sunlight onto each cell for maximum efficiency. It uses the concentrated sunlight to obtain a cost-effective solar energy. It can be operated at higher temperatures than conventional photovoltaic modules. Therefore, due to temperature increase, most of the absorbed solar energy converted to thermal energy. So, Photovoltaic thermal solar (PV/T) collectors describe the collectors that produce both electric and useful heat energy from solar cells. Increasing of cell temperature leads to a decrease in the electrical efficiency of photovoltaic systems. Adding cooler causes, the electrical and overall efficiency of a photovoltaic system to increase.

Different technologies were used for cooling the CPV modules. These technologies are:

- Floating tracking concentrating cooling (FTCC) or water spray [2-3],
- Forced air circulation [4-13],
- Phase-change materials (PCM) [14-17],
- Transparent coating (photonic crystal cooling) [18-19],
- Forced water circulation [20-28].

The FTCC uses a sprinkler to spray the whole surface area of CPV with water. Ref. [2] presented an approach to enhance the efficiency of luminescent solar concentrators using poly methyl methacrylate (PMMA) thin-films. 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 experimental data and showed good agreement. In FTCC method the sprinklers cannot coverall surface area of the CPV module, that means some parts only of it are cooled. Also, this method does not take advantage of hot water.

Concentrating photovoltaic (CPV) air cooling system is used to improve the maximum heat gain and spontaneous reduction of PV cell surface temperature by controlled air flow rate. The CPV air type collector is effective, and simple in operating and design. Refs. [4-5] developed a thermal model to a glazed CPV air cooling system for using it in space heating and drying purposes. Ref. [6] investigated the performance of a concentrating PV solar collector to improve the overall electrical and thermal efficiency of CPV system to 11% and 58%, respectively. Ref. [7] developed a model to evaluate the performance of PV module integrated with an air duct. The Results proved that there was an improve in overall efficiency. Refs. [8-9] determined the efficiency of different configurations of PV/T air collector. The results showed that the glass to glass PV with duct gave the highest 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 with and without air cooling was discussed in [10]. The results showed that the temperature of PV can be decreased 2-3°C with air cooling whereas the maximum output power can be increased by 6-14% after using air cooling. An experimental analysis of a photovoltaic-thermal air collector was performed in [11]. The results showed that the electrical and thermal efficiencies of the PVT collector 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 into air type CPV technology 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 heat from the CPV module during the melting process of the PCM. It can store large amounts of thermal energy with small temperature differences. Ref. [14] presented pure and combined PCM to investigate the electrical performance of the CPV module. Results proved that the electrical efficiency was increased by an average of 5.8%. Ref. [15] developed a model to predict melting and solidification fractions of the PCM, and applying that model increased both electrical energy (by 5.9%) and cost-effectiveness. Ref. [16] applied the ZnO/water nanofluid (0.2 wt%) and paraffin wax. The output thermal energy was increased by 48% with PCM/Nanofluid. Ref. [17] designed a novel concentrated photovoltaic thermal hybrid solar (PVT), collector. It involved two absorber plates painted by two selective surfaces (paints). The results showed that the thermal efficiency of the PVT design was more than 60% and the total efficiency of the PVT 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 (photonic crystal cooling) 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 enhances the efficiency of the PV panel [18]. The Micro-photonic design was used to cool PV panel through radiative cooling [18]. A modified three-dimensional metallic photonic crystal was used to match emission spectrum for the useful solar thermo-photovoltaic [19]. 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 electrical and thermal efficiency. It provides a hot water for domestic applications. The water-cooled CPV module performance was analyzed experimentally in [20]. 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. [21] presented an experimental and mathematical model for the PV heat pump to estimate the electrical efficiency, power generation of the PV modules and the coefficient of performance (COP) of the heat pump. Ref. [22] presented an experimental performance analysis for CPV with water cooling system. The results indicated that the temperature of the CPV module was reduced under 60°C using cooling water and therefore the performance of the CPV has improved.

Ref. [23] designed and fabricated an air and water cooling system to cool the PV panel to keep up the lower operating temperature. The drop in the temperature led to an increase in solar cells efficiency from9% to 14%. Ref. [24] presented an experimental analysis of a new type of PV/T solar systems composed of PV modules with water heat extraction devices. Ref. [25] presented a numerical model to analyze the performance of a hybrid PVT system. It investigated the impact of both solar cell packing and the water mass flow rate on the electrical and thermal efficiency. Ref. [26] presented hybrid photovoltaic thermal solar collectors. It was found that the thermal efficiency of hybrid PV/T system was in the range of 45% to 70%. The nature convection PV thermosyphon water heating system was applied with aluminum-alloy flat box to improve the electrical efficiency to 10.3~12.3% and the thermal efficiency to 37.6~48.6% in summer and winter [27-28].

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 small campus in Mansoura university, Egypt with electric and thermal energy are presented.

II. Mathematical Model of CPV/T System

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

(A) Solar radiation model

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

$$G = G_B + G_d \quad (1)$$

The beam irradiation on a horizontal surface can be expressed as [16]:

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

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

The solar altitude angle (α) is calculated from the following relation [29]:

$$\sin(\alpha) = sin\,\delta \sin L + cos\delta \cos L \cos h \quad (4)$$

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

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

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:

$$G_d = C_d G_{Bn} F_{ss} \quad (7)$$

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

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

(B) PV Model

The PV cell temperature can be expressed as a function of irradiation and concentration ratio as follows [30]:

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

The short circuit current depends on the concentration ratio C, solar irradiance G, and is also affected by the cell temperature as follows [30]:

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

The open circuit voltage is affected by the cell temperature as follows [17]:

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

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

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

Where V_T is the terminal voltage, equal to 0.0258 at the room temperature and a is the diode ideality factor no fix value between 1 and 1.5.

The relation between current and voltage of solar cell influenced by the temperature can be expressed as follows:

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

Also, the relation between power and voltage of solar cell influenced by the temperature can be expressed as follows:

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

The PV efficiency can be expressed as a function of cell temperature [31]:

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

(C) CPV efficiency model

The ideal thermal power absorbed by PV module can be obtained by [32]:

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

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

The electric efficiency is evaluated from the following equation:

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

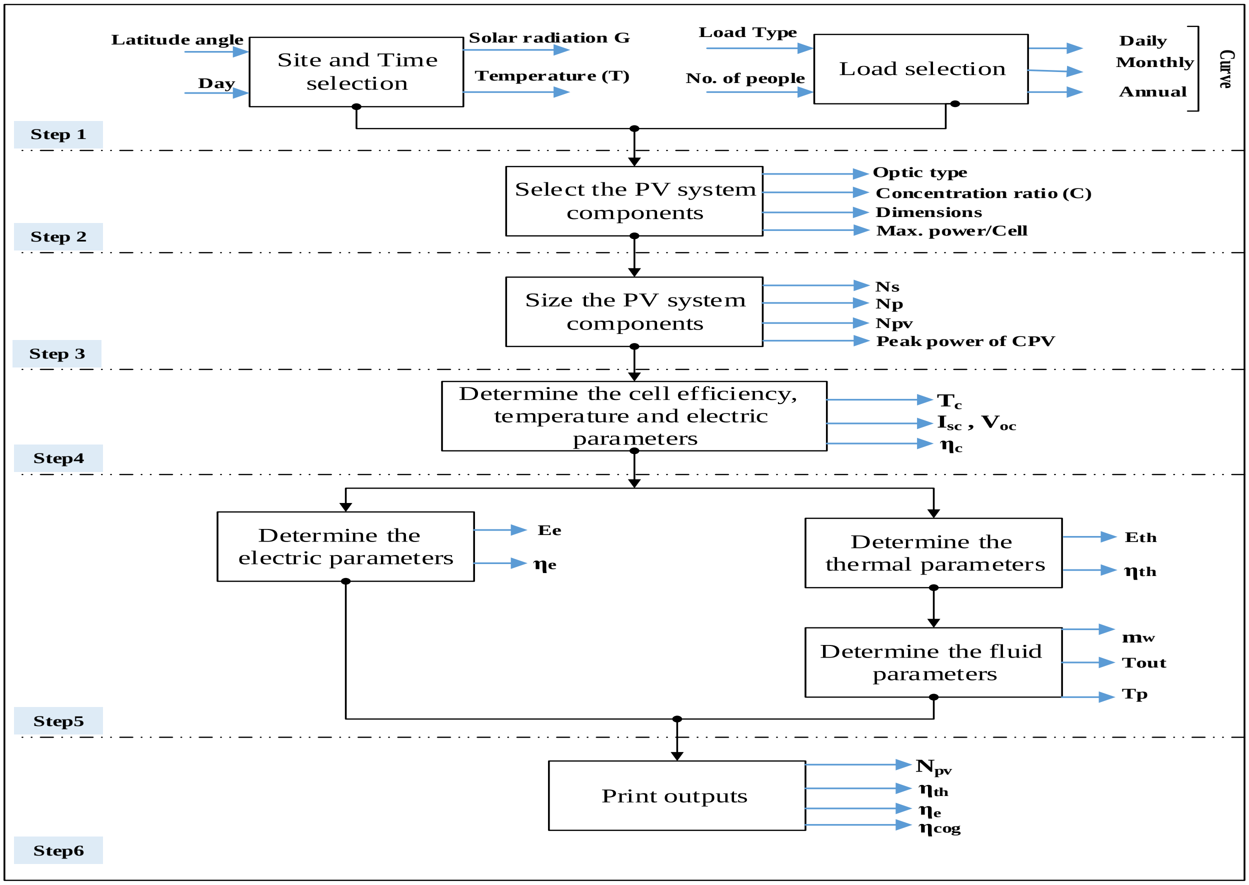

Fig. 1.Block diagram of design steps

Thermal efficiency is calculated by the following equation:

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

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

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

(D) Sizing the solar CPV System

The daily energy requirement from the solar PV array can be determined as following:

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

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 [33]:

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

The total current needed 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 modules can be determined 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 modules can be determined 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 equals the series modules multiplied by the parallel ones:

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

III. DESIGN PROCEDURE OF PV/T SYSTEM

The CPV/T model has been implemented in MATLAB 2014b [34]. Figure 1 shows the block diagram of the design steps. After the entering of the input values, the solar radiation and PV models are run to calculate the required parameters.

IV. DATA DESCRIPTION

The proposed model of CPV/T is evaluated using daily solar irradiance G. This irradiance was calculated at a selected location El-Mansoura (Egypt, long. 31.38° E, latitude 31°N). The calculations have been performed each 1 h, from 8 h to

16 h and that during successive day, February 21th. The hourly solar radiation on the test day (21th February) is expressed by Fig. 2 and the peak solar radiation at solar noon is 824 W/m^2.

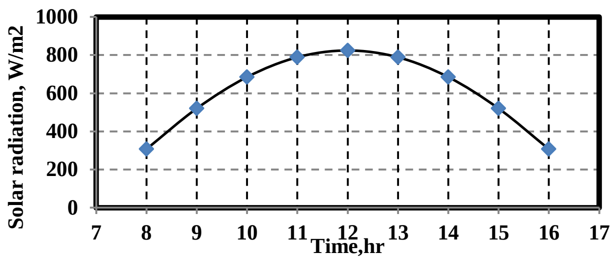

Fig. 2. Hourly solar radiation for (El-Mansoura City, Egypt) (21th February)

The monthly average daily values of diffuse solar radiation data incident on horizontal surface and on tilted surface (s=30°) at the considered site (small campus in Mansoura university, Egypt) at a location of 31° N latitude are illustrated in Fig. 3. The solar energy incident in the selected site is very high especially during the summer months, where it exceeds to 8 kWh/m^2/day on horizontal surface. The annual average daily value of diffuse solar radiation on a horizontal surface for this area is 6.36 (kWh/m^2/day).

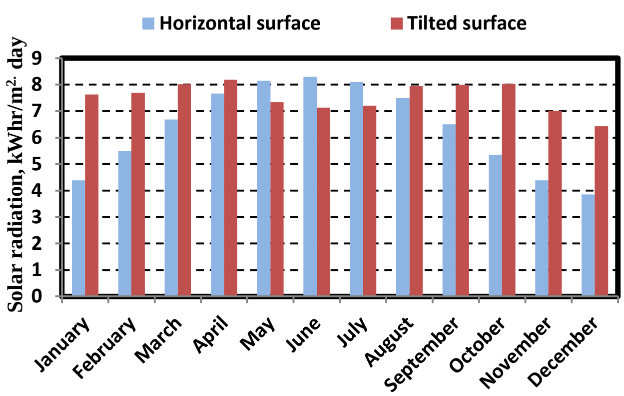

Fig. 3. Monthly average daily global radiation on a horizontal surface and on a 30o tilted plane at El-Mansoura, Egypt.

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 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.

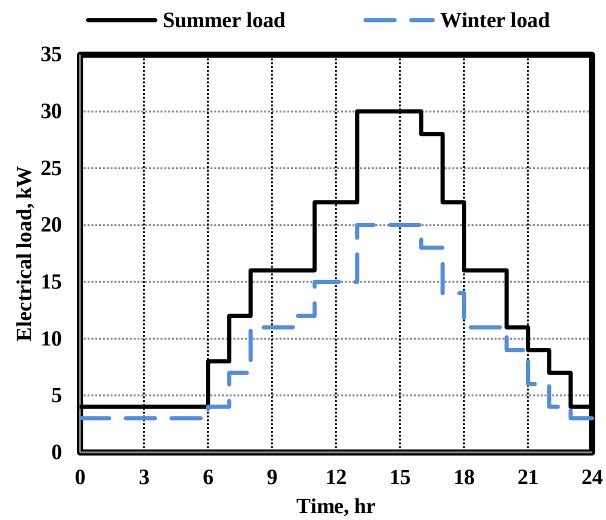

Fig. 4. Hourly electrical load of the small campus in summer and winter season

V. RESULTS AND DISCUSIONS

System sizing is the process of evaluating the adequate voltage and current ratings for each component of the photovoltaic system to meet the electric demand at the facility. The select panel is a SPT250-20WC and the specification of PV panel is shown in Table I.

TABLE I
THE SPECIFICATION OF PV PANEL

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

The proposed algorithm was applied on the site and load data using a 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 solar cell and the concentration solar cell CPV with time are shown in Fig.5. The temperature of flat solar cell and the temperature of the concentration solar cell (C=2) have been reached to maximum at the solar noon time. As shown in Fig. 5, the maximum temperature difference between the concentration solar cell and the flat solar cell was lower than 27.8^{o}C. The average temperature difference was about 17^{o}C.

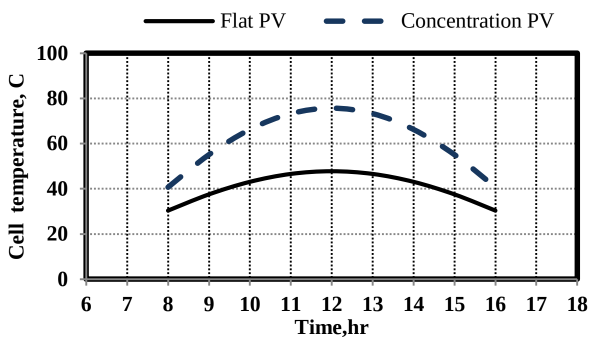

Fig. 5. Solar cell CPV and flat temperature with respect to day time

The electrical efficiency of the flat solar cell and the concentration solar cell CPV using cooling water during the day (February 21th) at C=2 are shown in Fig.6. The average electrical efficiency of the flat PV and the CPV using cooling water are 10.18% and 13.2%, respectively as shown by Fig. 6. Also, it is observed that the solar PV cell performance with cooling and concentration ratio is much higher than the fixed solar cell under the same input conditions.

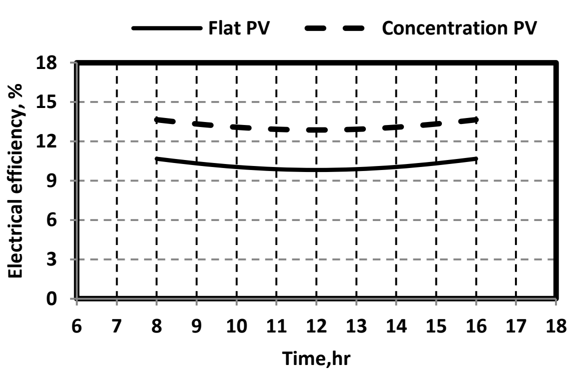

Fig. 6. Electrical efficiency of CPV and flatPV with respect to day time

Figs. 7 and 8 show the effect of water flow rate 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. 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.

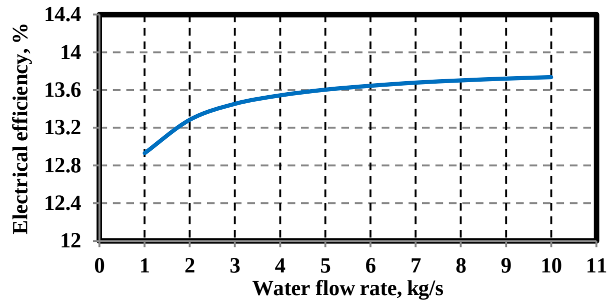

Fig.7 Electrical efficiency versus water mass flow rate at G=800 W/m2 and C=2

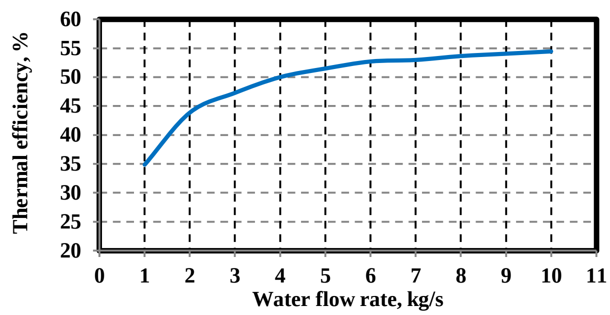

Fig. 8 Thermal efficiency versus water mass flow rate at G=800 W/m2 and C=2

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

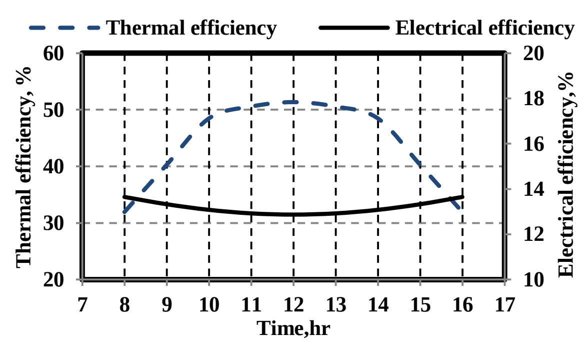

Fig. 9. PV modules electrical efficiency and thermal efficiency of CPV (C=2)

The thermal, electrical and cogeneration efficiencies of the concentration solar cell (C=2) at hot water outlet 50 ^{o}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.

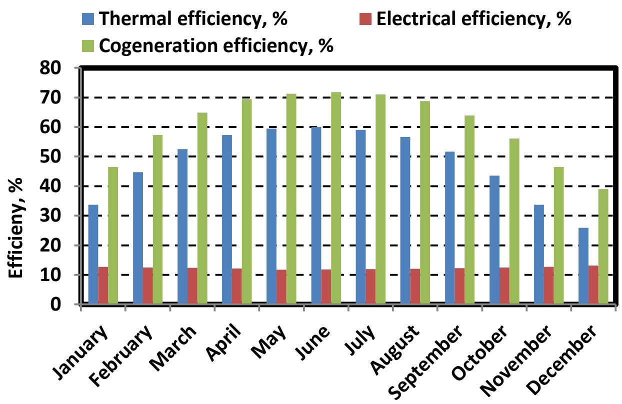

Fig. 10. The thermal, electrical and cogeneration efficiencies of the concentration solar cell at C=2 and Tout= 50oC.

The Daily mass of hot water at C=2 and different outlet hot water temperature (40, 45, and 50 ºC) are shown in Fig. 11. As can see, the average daily mass of hot water during the year is 53.57 ton at 50ºC, 62.22 ton at 45ºC and 77.78 ton at 40ºC.

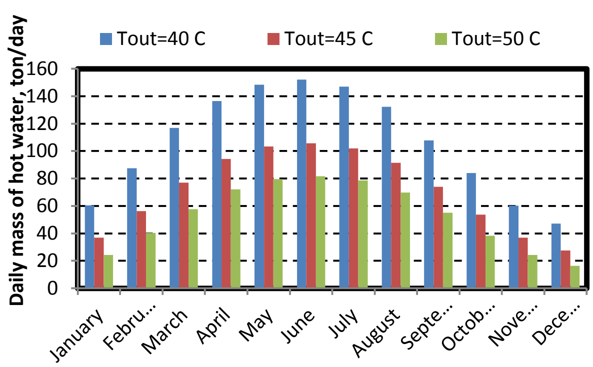

Fig. 11. The average daily mass of hot water at different outlet hot water temperature and C=2.

The average daily of electrical energy output at C=2 and different outlet hot water temperature are shown in Fig. 12. As can see, the average daily electrical energy during the year is 449.77 kWh at 50ºC, 457.1 kWh at 45 ºC and 462.19 kWh at 40 ºC.

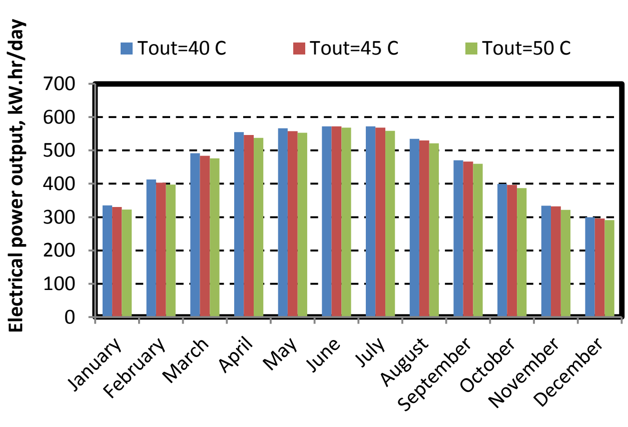

Fig.12. The average daily of electrical energy output at different outlet hot water temperature and C=2.

VI. Conclusions

In this work, theoretical performance analysis of a CPV/T module 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 university – Egypt is 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 cooling and concentration ratio was much better than the fixed solar cell under the same input 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 CPV/T system. The average cogeneration efficiency of the CPV/T system reached up to 60.52 %.
5- The electrical and thermal energy output of CPV/T system is increased by increasing the water mass flow rate.

Nomenclature

A_c	Cell area, m^2
A	Apparent solar irradiation at air mass zero ,W/m^2
a	Diode ideality factor
B	Atmospheric extinction coefficient
C	Concentration ratio
C_d	Diffuse radiation factor
C_p	Fluid specific heat, J/kg. ºC
E_L	Daily average energy consumption, kW.hr/day
F_{ss}	Angle factor between the surface and the sky
G	Solar radiation, W/m^2
G_B	Beam solar irradiation, W/m^2
G_d	Diffuse solar irradiation, W/m^2
G_{Bn}	Normal beam solar irradiation, W/m^2
h	Hour angles
hc	Convective heat transfer coefficient, W/m^2.ºC
I	PV current, Ampere
I_o	Diode saturation current, Ampere
Isc	Short circuit current, Ampere
I_{DC}	Total module current, Ampere
I_r	Rated current of one module, Ampere
k	Thermal conductivity of plate, W/m.ºC
k_l	Thermal conductivity of fluid, W/m.ºC
L	Latitude angle
L_c	Characteristics length, m
$\dot{m}$	Mass flow rate of cooling water, kg/s
n	Day number
N_{pv}	Total number of modules
N_p	Number of parallel modules
N_s	Number of series modules
NOCT	Nominal operating cell temperature,ºC
P	Power of cell, W
P_{pv}	Peak power of modules, W
Q_{th}	Rate of thermal energy, W
$Q_{th,a}$	Actual rate of thermal energy, W
S	Surface tilt angle
T	Thickness, m
T_c	Cell temperature, ºC
T_{amb}	Ambient temperature,ºC
T_p	Plate temperature, ºC
T_{in}	Inlet water temperature,ºC

T_{out}	Outlet water temperature, ºC
u	Fluid velocity, m/s
V	PV voltage, volt
v_{oc}	Open circuit voltage, volt
V_{DC}	System DC voltage, volt
V_r	Module rated voltage, volt

GREEK SYMBOLS

α	Solar altitude angle
δ	Declination angle
Δ	Difference
ρ	Fluid density, kg/m^3
μ	Fluid dynamic viscosity, Pa.s
ε_C	Cell emissivity ,$\varepsilon_C = 0.85$
σ	Stefan Boltzman constant equal to 5.670373×10^{-8} $W/m^2.K^4$.
η_{th}	Thermal efficiency, %
η_e	Electrical efficiency, %
η_o	Overall efficiency, %
η_{cog}	Cogeneration efficiency, %
η_{bat}	Battery efficiency, %
η_{cab}	Cable efficiency, %
η_{reg}	Regulator efficiency, %
η_{inv}	Inverter efficiency, %
η_{opt}	Optical efficiency, %

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