

Efficiency Improvement of the Hybrid PV/T System Applied on Kuwait

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Abstract— This paper presents a novel model and performance evaluation of a low concentrating photovoltaic (CPV) and photovoltaic/thermal system CPV/T systems to improve the efficiency of the PV systems. Two types of reflective optics are used with V-trough and parabolic mirror concentrators of point focus type and the triple-junction cells (InGaP/InGaAs/Ge) assembled to obtain a low and high concentration system. The proposed model was built in the MATLAB/Simulink environment by considering constant PV cell temperature. The model adopts a mathematical approach in order to simulate and investigate the cell characterization curves including module electric and thermal efficiencies, thermal and electric energies provided by cell and module, and cooling fluid temperatures. Also an active cooling system of the photovoltaic cells is considered. The model analyzes the CPV and CPV/T system working for different time levels in terms of direct normal irradiance. The comparison of these systems operating confirmed the improvement of the electrical performance of the concentrating photovoltaic/thermal system.

Index Terms— Modeling of PV, Concentrating PV system, Hybrid CPV/T system.

1 INTRODUCTION

The main types of solar power systems are divided into: solar thermal systems and solar PV systems. Solar thermal system is used in generating electricity by heating water which has low efficiency. PV systems generating electric energy directly from sun light. They differ from small, roof-top mounted or building-integrated systems with capacities from a few to several tens of kilowatts, to large utility-scale power stations of hundreds of megawatts [1-2].

Amongst the various different photovoltaic technologies (monocrystalline, polycrystalline and thin film technologies), the latest at present is concentrated photovoltaic, commonly known as CPV. It is used to describe systems that combine photovoltaic (PV) cells with an optical component that concentrates light. Hybrid photovoltaic/thermal (CPV/T) solar systems are less expensive devices than the two separate units which can simultaneously provide electricity and heat with higher conversion rates of the absorbed solar radiation than standard PV modules [3-4]. By concentrating the radiation through magnification, the intensity of solar radiation may be increased by several times or several hundred times of its standard output [5]. The required cell area for producing a given amount of power and the cost of electricity produced from the CPV/T system will be reduced by replacing expensive PV converter area with less expensive optical material. This approach provides the opportunity to use higher performance PV cells [6]. These characteristics could make CPV/T to be the most widely used solar energy for large generating plants.

Many researches and developments on modeling of CPV/T has been promising during the last decade [7-12]. Ref [7] characterizes experimentally the thermal and electrical performance of a 2m² PVT system. The performance evaluation

and response of PV cell parameters of low level of concentration were presented in [8]. Ref [9] considered a PV/T collector of various geometric shape designs, and operating characteristics and discussed the effect of non-uniform flow distribution on the thermal and electrical performance of their solar systems. Ref [10] studied and designed low CPV and (PV/T) and the tests for a given spring climatic condition of the Tunisian Saharan city Tozeur then developed and validated against the experimental results. Ref [11] presented the design, modeling and performance evaluation of a photovoltaic/thermal-assisted heat pump water heating system. It studied the cooling effect of enhances the PV/T efficiency and effectively improves the coefficient of performance. Ref [12] studied the effect of the collector area covered by PV module on the performance of hybrid PV/T water collector. They considered two configurations in which the collector is partially and fully covered by PV module and compared their results with those of a conventional flat plate collector. In [10] a CPV/T system has been linked to a single stage LiBr/H₂O absorption heat pump, realizing so a solar cooling system. Moreover, it is important to adopt an apparatus that allows both to chase the solar radiation and the right location of the pipes where the heat transfer fluid flows without occupying too much space [11].

2. CONCENTRATING PHOTOVOLTAIC TYPES

The optical components, which are also called optical concentrators, are designed to harvest sunlight from a wide area and focus it directly onto a small area covered by PV cells. This increases the intensity of the light reaching the PV cells, which in turn increases the amount of power the cells can produce.

Concentrating photovoltaic CPV systems consist primarily of an optical concentrating element which could be a Fresnel lens, parabolic troughs dishes, V-trough mirrors, luminescent glass, refractive prism or a compound parabolic concentrator. Other elements of the system include solar cells and a heat

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dissipation system [1]. These types depend on the type of sunlight focus and receiver, and classified, according to the concentration factor, in plants at low, medium and high concentration [12]. In this paper we study two types of the optical concentrating elements; V-trough mirrors and parabolic trough dishes.

2.1 Low concentration system with V-trough

In the CPV systems the solar radiation is concentrated by means of optical devices that allow to decrease the solar cells area proportionally to the concentration factor [4]. The basic concept of li concentration by reflective or refractive means is conceptually simple and straightforward. Figure 1 shows the basic concentrator configuration of the V-trough reflector. In Figure 2 some rather tedious but straight forward calculations indicate that the concentration ratio of the V-trough concentrator is [12].

$$C = 1 + \frac{2 \sin \theta_m \cos(\theta_i + 2\theta_m)}{\sin(\theta_i + \theta_m)} \tag{1}$$

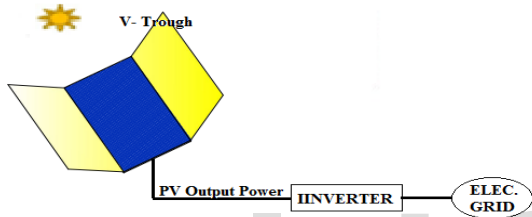


Fig. 1 Block diagram of V-trough PV system

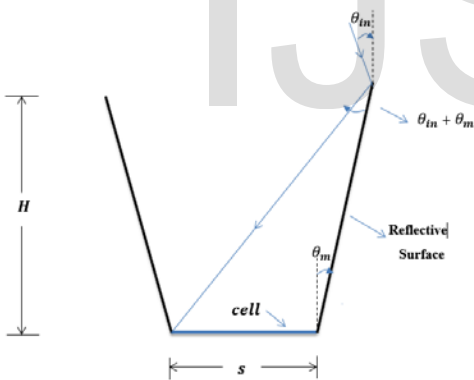


Fig. 2 Basic V- trough concentrator

2.2 High concentrating with Parabolic

In CPV systems the solar radiation is concentrated by means of optical devices that allow decreasing the solar cells area proportionally to the concentration factor [12]. The active cell area is the region of the cell that is designed to be illuminated. Unlike in most non-concentrating systems, the entire cell need not be illuminated by the primary lens. The non-illuminated edge of the cell is often provided with bus bars for electrical connection, and this need not result in an efficiency loss as would be the case in a flat-plate module. Parabolas have the property that, if they are made of material that reflects light, then light which enters a parabola travelling parallel to its axis of symmetry is reflected to its focus; regardless of where on the parabola the reflection occurs [6]. A basic concentrator configuration is the reflective parabolic concentrator

shown in Fig. 3.

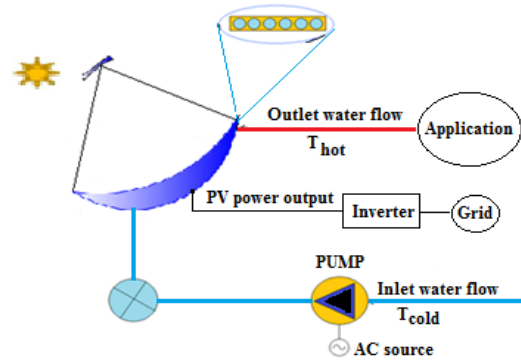


Fig. 3 Block diagram of CPV/T system

The two-dimensional cross section is shown, which could represent the cross section of either a two-dimensional linear parabolic trough or the cross section of a three-dimensional parabolic of revolution [6].

The equation relating the x and y components of the parabolic surface is [6, 13]

$$y = \frac{1}{4} Fx^2 \tag{2}$$

Where F is the focal length of the parabola. It can be shown that all rays coming from straight up will pass through the focus; D is the diameter or width of the parabola. For a two-dimensional parabolic trough, the concentration ratio is given by equation below [6, 13].

$$C = \frac{\cos \theta_{r,max} \sin \theta_{r,max}}{\sin \theta_{i,max}} \tag{3}$$

Where $\theta_{i,max}$ is the maximum incident angles and $\theta_{r,max}$ is the maximum reflection angles on the edge (rim angle), that the maximum concentration for a parabola at $\theta_{r,max}$ equal 45° at $f = 0.6$, where f is called the f-number of the parabola [6, 13].

Noting that the total receiver size, S required to capture all rays up to incident angles of $\pm \theta_{in,max}$ [6, 13].

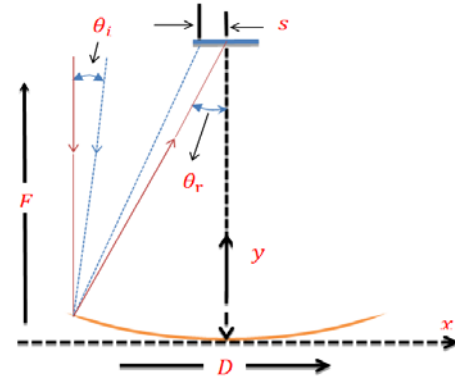


Fig. 4 Basic parabola concentrator

3. DESIGN PROCEDURE OF CPV/T

In order to analyze the system proposed under various operating conditions, the main system variables (optics, cell size, concentration factor and loads) have been suitably varied. The CPV/T system model has been realized in Matlab and divided into several steps as shown in Fig. 5.

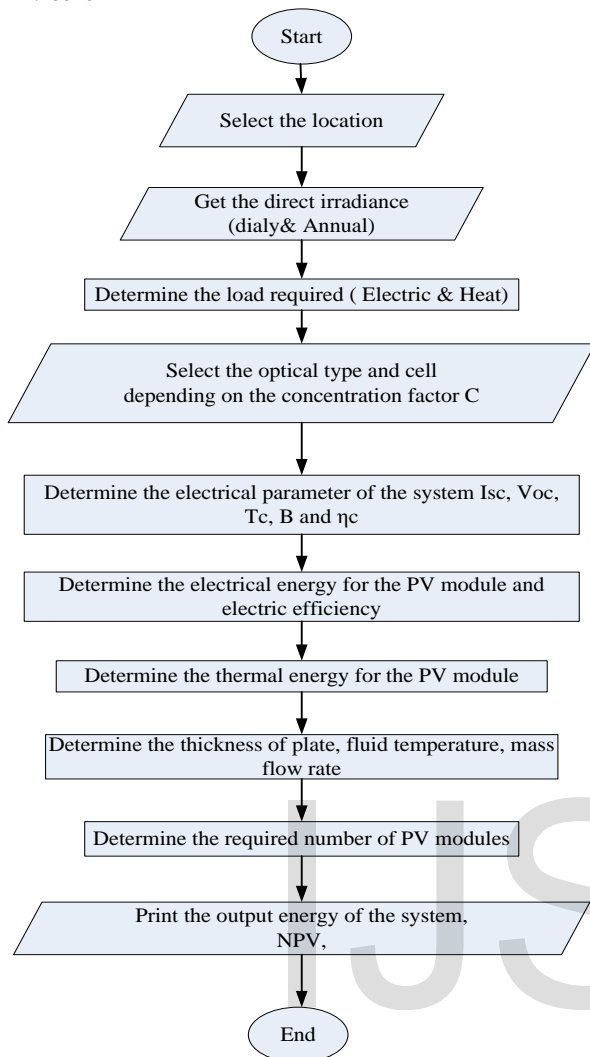


Fig. 5 Flow-chart of the design steps of CPV/T system

4. MODELING OF CONCENTRATING PV SYSTEMS

Both the low concentration system with V-trough mirror and the high concentration system with parabola optics are modeled and simulated in the next sections.

4.1 PV with V-Trough concentrator

To study the effect of concentrators on PV characteristics, Simulink model was performed for the MSX-60 PV [15] cell with a V-trough concentrator. The module photo-current can be modified for concentration according to the module photo-current equation:

$$I_{ph} = [I_{sc} + K_i(T - T_{ref})]C * G/1000 \quad (4)$$

Where C is the concentration ratio given by equation (1) and TC is the new cell temperature due to increased radiation with C factor.

The new model can be performed similar to the solar panel model [14], but with the new equations. There is a new equation for the concentration ratio C. The block diagram of it is shown in Fig. 6 other equations can be modeled by the same block diagrams as in [14] but with the new values of tempera-

ture and radiation.

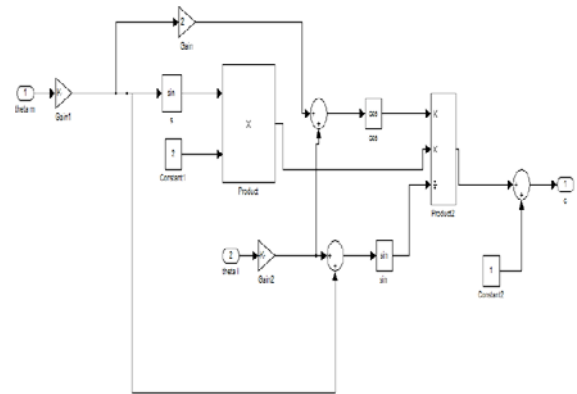


Fig. 6 Concentration ratio model

A subsystem for the concentrator that gives the new values of radiation and temperature is shown in Fig. 7.

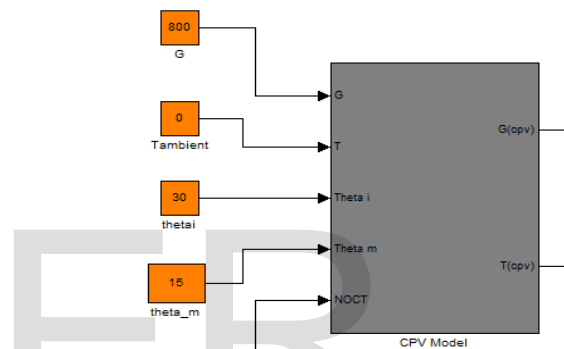


Fig. 7 V-trough concentrator model

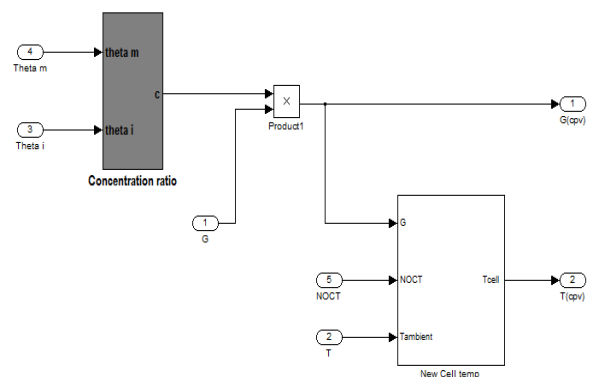


Fig. 8 Circuit of concentrator model

4.2 Hybrid Concentrated Thermal CPV/T System

In CPV/T systems the production both electricity and thermal energy is the main priority, where it is necessary to operate the PV modules at low temperature in order to keep PV cell efficiency at a sufficient level. Where under high concentration ratio the temperature increasing where 1400°C can be achieved at concentration ratios around 500 suns [15]. The CPV/T systems can use various cooling techniques for cooling cells under high concentration.

In the part of The CPV/T the system used consists of multi junction (InGaP/InGaAs/Ge) cell and optical device which is parabolic concentrators which has high concentration ratio and temperature so it uses active cooling system, which is consisting of water pipes. The CPV/T module is connected electrically with load and the thermal energy is used for demonstrated application as shown in Fig.3. The CPV/T system produces electrical and thermal energy, and each type of energy product is calculated by a separate equations

A. Electrical Energy

- Cell electrical power (P_c)

For using a concentration system, the electrical power produced by a single cell can be calculated from the equation below [12]:

$$P_c = \eta_c \cdot \eta_{opt} \cdot A_c \cdot C \cdot G_{ind} \cdot f \quad (6)$$

Where G_{ind} is the direct irradiance per hour, A_c is the area in m², and f is the non-ideal tracking system factor and equal 0.9 [12]. η_c and η_{opt} are the cell efficiency and the optical efficiency. The optical efficiency is depending on the type of mirror used and its state of cleanliness. A clean mirror made of low-iron glass with a silver back-coat should provide a reflectivity of 90-94% [17]. We will use a concentration ratio of a few hundred and optical efficiency η_{opt} equal to 0.85 typical values for parabolic concentrators [17]. The cell efficiency varies with concentration C and cell temperature T_c according to the equation (7):

$$\eta_c = 0.298 + 0.0142 \cdot \ln(C) + (-0.000715 + 0.0000697 \ln(C))(T_c - 25) \quad (7)$$

- Actual electrical power ($P_{c,a}$)

The actual electric power delivered by cell ($P_{c,a}$) is given by the equation below [18]:

$$P_{c,a} = K_t \cdot P_c \quad (8)$$

Where, K_t is the correction coefficient for temperature when the standard temperature is set to 25°C and can be calculated by equation below [18].

$$K_t = 1 + a(T_c - 25) \quad (9)$$

Where a is the normalized temperature coefficient and depend on cell type and manufacturer; analyzing many data sheets a value equal to -0.16% has been selected [12]. $(T_c - 25)$ is the deference between the cell temperature and the rated temperature (25 C°).

- Ideal module electric power (P_{mod})

Additional module losses are caused by some unavoidable spaces among the cells by front contacts that shade the cell active area, and by current mismatch due to differences in the output of cells connected in series. The electric power produced by the module can be obtained by equation below:

$$P_{mod} = P_{c,a} \cdot N_c \cdot \eta_{mod} \quad (10)$$

Where η_{mod} is the efficiency of module and fixed to 0.9 and N_c is the cell number.

- Actual module electric power ($P_{mod,a}$)

The inverter performs the conversion of the produced DC to AC, and synchronizes the output of the PV system to the grid frequency [19]. If cell linked in series the actual electric power is given by the equation below [12]:

$$P_{mod,a} = (P_{mod} - P_{par}) \cdot \eta_{inv} \quad (11)$$

Where η_{inv} is the inverter efficiency depends on its size and other parameters; we use a typical value of η_{inv} equal to 0.9 and P_{par} is the module losses given by the equation below [17]:

$$P_{par} = G_{par} \cdot G_{ind} \cdot A_c \cdot C \cdot N_c \quad (12)$$

Where G_{par} is the losses factor depending on the radiation, and equal to 0.0023 [7].

- Efficiency of the PV module (η_{pv})

The module efficiency under incident flux of 1 kW/m² (one sun), accounting for the variation of the cell efficiency with the cell temperature, and concentrating photovoltaic module overall efficiency given by equation below [18]:

$$\eta_{pv} = \eta_c \cdot \eta_{mod} \cdot K_t \quad (13)$$

B. Thermal Energy

- Ideal thermal power delivered by the PV module (Q_{th})

For larger concentrators, the fraction of parasitic power is expected to be smaller. The incident power is the beam irradiation flux multiplied by the overall collector aperture area. The thermal power absorbed by the receiver can be obtained by equation below [12]:

$$Q_{th} = (1 - \eta_{pv}) \cdot \eta_{opt} \cdot C \cdot (G_{ind} \cdot f) \cdot A_c \cdot N_c \quad (14)$$

- Actual thermal energy transferred to the coolant ($Q_{th,c}$)

Thermal energy is equal to the difference between the theoretical total thermal energy and the radiative and convective losses generally included in the range 1-3% [12], and given by the equation:

$$Q_{th,c} = Q_{th} - Q_L \quad (15)$$

Where Q_L is the thermal loss which includes a convection coefficient based on a representative wind of 5 m/s [19]. So the heat loss through radiation and natural convection is given by equation [21]:

$$Q_L = [\bar{h}_c \cdot (T_c - T_o) + \varepsilon_c \cdot \sigma \cdot (T_c^4 - T_c^4)] \cdot A_c \cdot N_c \quad (16)$$

Where ε_c is the cell emissivity and equal to 0.85 and \bar{h}_c equal to 10 w/m²k and σ is Stefan Boltzman constant equal to 5.670373×10⁻⁸ W/m². k⁴ [19].

- Fluid temperature (T_{out})

The variation of thermal energy output relative to the fluid input temperature T_{in} and outlet temperature T_{out} and is given by equation below [7]:

$$\dot{Q}_{th,c} = [\dot{m} \cdot C_p \cdot (T_{out} - T_{in})] \quad (17)$$

Where \dot{m} is the fluid mass flow rate and C_p is the fluid specific heat, for water equal to 4180 J Kg⁻¹ K⁻¹. Hence the outlet fluid temperature can be obtained by equation below [12]:

$$T_{out} = T_p - [T_p - T_{in}/e^{(h_c A_c)/(m_c)}] \quad (18)$$

Where h_c the convection heat is transfer for water equal to $150 \text{ w/m}^2 \cdot \text{C}^\circ$ and A_c is the heat exchanger areas. In particular, the sun rays focused on the triple-junction cell allow the heating of the absorber plate, the equation that regulates the exchange between the cell and plate [12], is defined as:

$$T_p = T_c - \left[\dot{Q}_{th,c} \cdot \left(\frac{d}{N_{C,A_c,k}} \right) \right] \quad (19)$$

Where k the conductive conductance depending on the heat exchanger type and d is heat exchanger thickness.

C. Overall efficiency of CPV/T

The overall efficiency of the system can be analyzed by determination of the different losses during the conversion from incident sunlight to the electric and thermal energy produced. The system produces electric and thermal energy and each of them has separate efficiency.

- **Electrical efficiency (η_{ele})**

The electric efficiency described by the efficiency of CPV/T to product the electricity from the sunlight. It can be calculated based on subsystem efficiencies as described:

$$\eta_{ele} = \eta_{opt} \cdot \eta_{pv} \cdot \left(1 - \frac{P_{par}}{P_c} \right) \cdot \eta_{inv} \quad (20)$$

- **Thermal efficiency (η_{Th})**

For thermal energy product the conversion efficiency is:

$$\eta_{Th} = \eta_{opt} \cdot (1 - \eta_{pv}) \cdot \left(\frac{Q_{th,c}}{Q_{th}} \right) \quad (21)$$

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

$$\eta_{CPV/T} = \eta_{ele} + \eta_{Th} \quad (22)$$

The CPV/T is simulated using the MATLAB/SIMULINK. The mathematical model of the CPV/T which is discussed in the previous section is simulated and the proposed Simulink model of the CPV/T is shown in Fig. 9. This model consists of subsystems to determine the variables of the system. The model determines the values of electric and thermal energy and efficiency of the CPV/T system as a function of hourly time and will be illustrated in figures from 10 to 21.

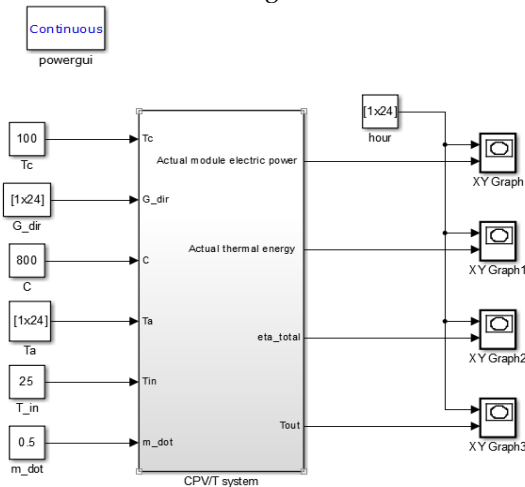


Fig. 9 Overall block diagram of the CPV/T model

of electric and thermal energy and efficiency of the CPV/T system as a function of hourly time.

Step 1: calculates the power produced by a single cell as shown in Fig. 10, according Eq. 6.

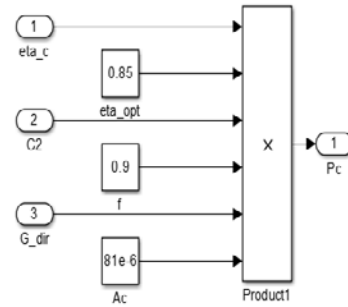


Fig. 10 Cell electric power

Step 2: calculates the actual electrical power ($P_{c,a}$) as shown in Fig. 11, according to Eq. 8 and Eq. 9.

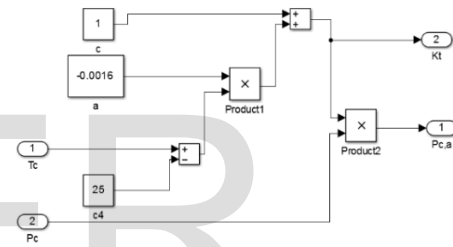


Fig. 11 Actual electric power.

Step 3: calculates the ideal module electric power as shown in Fig. 12, according Eq. 10.

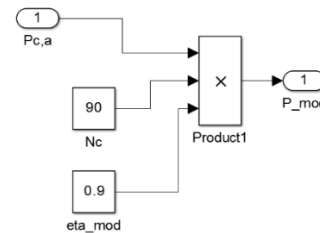


Fig. 12 Ideal module electric power P_mod

Step 4: calculates the actual module electric power as shown in Fig. 13, according to Eq. 11.

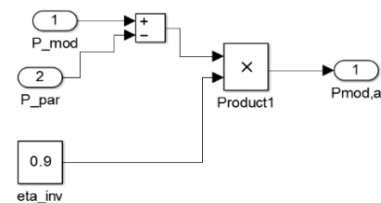


Fig. 13 Actual module electric power ($P_{mod,a}$)

This model consists of subsystems to determine the values

Step 5: calculates the module losses P_{par} as shown in Fig. 14, according to Eq. 12.

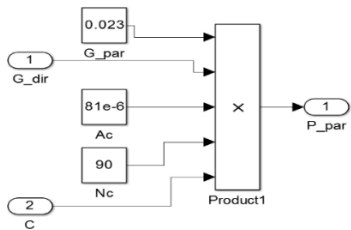


Fig. 14 Module losses P_{par}

Step 6: calculates the module efficiency (η_{pv}) as shown in Fig. 15, according to Eq. 13.

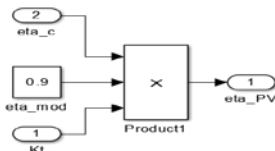


Fig. 15 Module efficiency (η_{pv})

Step 7: calculates the ideal thermal power delivered by the PV module (Q_{th}) as shown in Fig. 16, according to Eq. 14.

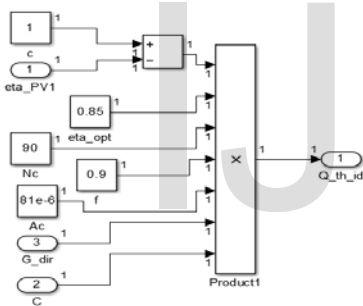


Fig. 16 Ideal thermal power (Q_{th})

Step 8: calculates the thermal loss (Q_L) as shown in Fig. 17, according to Eq. 16.

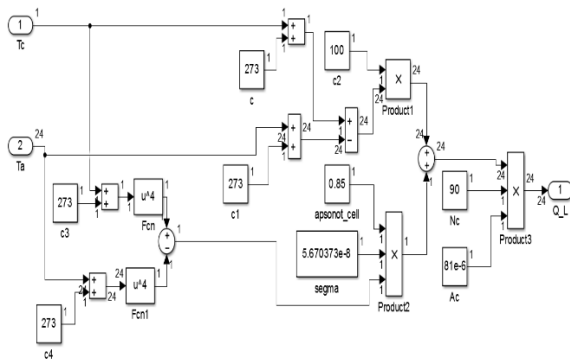


Fig. 17 Thermal loss (Q_L)

Step 9: calculates the fluid temperature (T_{out}) as shown in Fig. 18, according to Eq. 18.

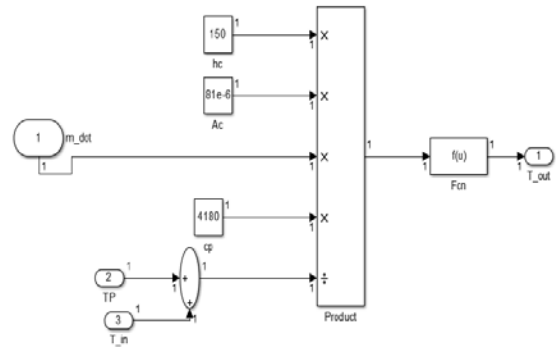


Fig. 18 Fluid temperature (T_{out})

Step 10: calculates the electrical efficiency (η_{ele}) as shown in Fig. 19, according Eq. 20.

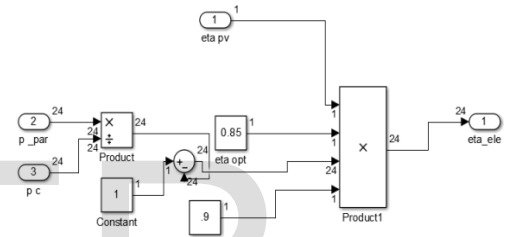


Fig. 19 the electrical efficiency (η_{ele})

Step 11: calculates the thermal efficiency (η_{Th}) as shown in Fig. 20, according to Eq. 21.

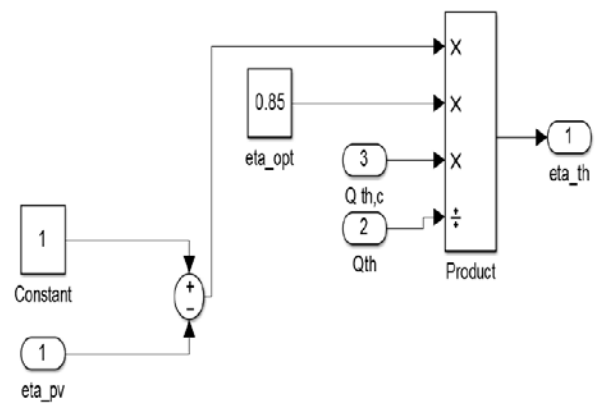


Fig. 20 Thermal efficiency (η_{Th})

All the above circuits are interconnected as shown in Fig. 21 to construct the model of the CPV/T.

5.2 Results of the Hybrid CPV/T system

The proposed model of CPV/T is evaluated using daily direct normal irradiance G_{ind} . Fig. 26 shows the value of the direct normal irradiation every hour along one day in June in Kuwait [20].

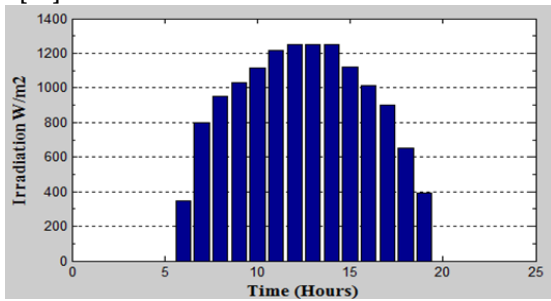


Fig. 26. Direct normal irradiance and Temperature for 24 hours

The input data of the proposed CPV/T Simulink model are daily irradiance, ambient temperature, size and number of cells, concentration factor and cooling system parameters. These data are illustrated in table 1.

Table 1 CPV/T system parameters

Parameter	Values
Number of cells N_c	90
Area of cells A_c	81×10^{-6} m
Type of optic	optical efficiency 0.85
Concentration factor C	1: 900
Cell temperature T_c	100 C°
Trucker system efficiency f	0.9
Temperature coefficient a	-0.0016
Module Efficiency η_{mod}	0.9
losses factor G_{par}	0.023
Inverter efficiency η_{inv}	0.9
Fluid specific heat C_p	For water 4180 JKg ⁻¹ K ⁻¹
Fluid input temperature T_{in}	25 C°
Cell emissivity ϵ_c	0.85
Stefan constant σ	5.670373×10^{-8} W/m ² .k ⁴
Convection heat transfer h_c	For water 150 W/m ² .C°
Conductive conductance k	For copper 384 W/m.k
Heat exchanger thickness d.	2×10^{-3} m

From the simulation data, it is found that, the model presented allows varying the input conditions for different time intervals (hourly), then the CPV/T system according to the site and energy demands. In Fig. 27 the electric power and efficiency of a CPV/T module with C equal to 800 referring to irradiation intensity in Fig. 26 are reported related to the reflective optics. A maximum power of 1560 W is measured at about 13. Moreover, the thermal daily power of the CPV/T module obtained from the model has been illustrated in Fig. 28.

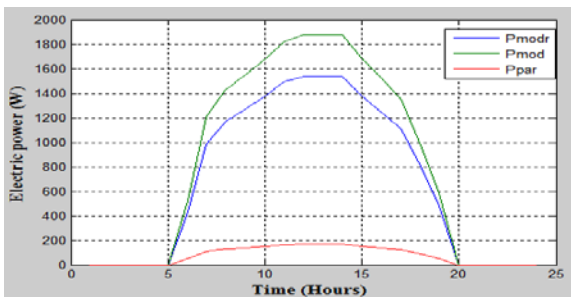


Fig. 27 Electric power of CPV/T module at C= 800 suns and TC=100°C



Fig. 28 Thermal power of CPV/T module at C= 800 suns and TC=100°C

In the same working conditions the electric and thermal efficiency of the CPV/T system increased by increase the concentration factor as shown in Fig. 29 and 30.

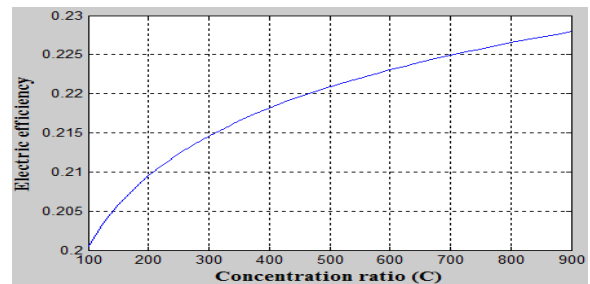


Fig. 29 Electric efficiency as a function of the concentration factor and TC=100°C

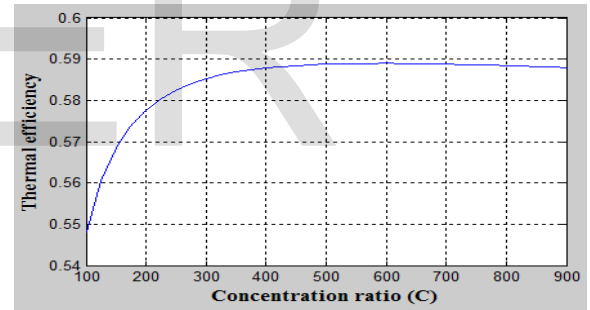


Fig. 30 Thermal efficiency as a function of the concentration factor and TC=100°C

Increasing the concentration factor C the output fluid temperature will increase as shown in Fig. 31 at constant water mass flow $\dot{m} = 0.015$. By increasing concentration factor C the water mass flow was increased as shown in Fig. 32 at constant output fluid temperature $T_{out} = 80^\circ\text{C}$.

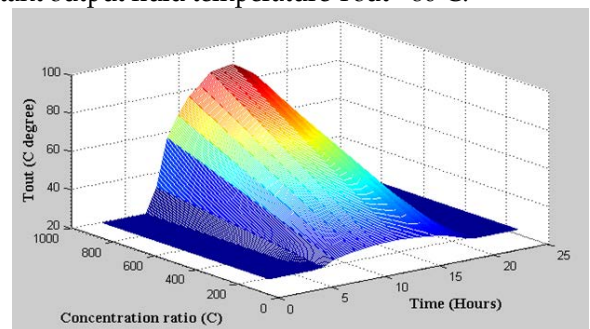


Fig. 31 Relation between the out let fluid temperature, the concentration factor and time during a day

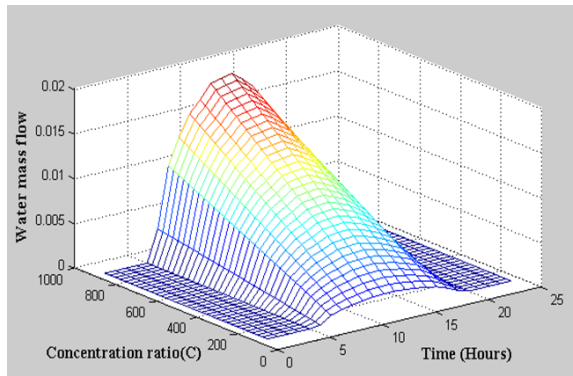


Fig. 32 Relation between the water mass flow, the concentration factor and time during a day

VI. CONCLUSION

This paper presents a model of both low concentrating photovoltaic V- trough (CPV) and high concentrated photovoltaic/thermal system (CPV/T) and simulate them using the MATLAB program. It includes modeling of the reflective optics with V trough and parabolic Concentrator. The electrical and thermal energy production of these systems has been monitored in different valued of irradianations. The model allows evaluating the values of the electric and thermal energy of the concentrating photovoltaic thermal (CPV/T) system (hourly). The results showed that the CPVT system gives higher electrical and thermal power outputs and efficiencies at the highest concentration factor. Also the model can obtain the relation between the water mass flow, outlet fluid temperature and the concentration factor.

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