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EXERGY AND CARBON CREDITS FOR SERIES CONNECTED N PHOTOVOLTAIC THERMAL - COMPOUND PARABOLIC CONCENTRATOR (PVT-CPC) COLLECTOR: AT CONSTANT OUTLET TEMPERATURE

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ABSTRACT

In the present study, overall energy and exergy performance of partially covered N photovoltaic thermal - compound parabolic concentrators (PVT-CPC) (25% covered by glass to glass PV module) collector connected in series have been carried out at constant outlet temperature mode. Further, comparison in performance for partially covered N photovoltaic thermal - compound parabolic concentrators (PVT-CPC) [case (i)] and N compound parabolic concentrators (CPC) collector [case (ii)] connected in series have also been carried out by considering a fluid namely ethylene glycol for high thermal performance. It has been observed that [case (ii)] are most suitable for steam and space heating whereas [case (i)] for thermal along with electrical need on the basis of comparative study. The maximum net annual overall thermal energy and exergy for N-CPC collector [case (ii)] which are higher than for N PVT-CPC collectors [case (i)] by 1.5 and 1.3 times, respectively. The kWh per unit cost based on exergoeconomic parameter or exergetic cost for [case (ii)] and [case (i)] has been found to be 0.054 kW h/Rs. and 0.036 kW h/Rs. for 30 years lifecycle with 2% interest, respectively. It has also been observed the environmental cost of [case (ii)] for overall thermal energy is 673.35 \$/tCO$_2$e and for overall exergy is 115.89 \$/tCO$_2$e for 30 yrs.

KEYWORDS: PVT, CPC, working fluid: ethylene glycol, annual energy and exergy.

I. INTRODUCTION

Photovoltaic thermal (PVT) hybrid collector produces both thermal and electrical gain. The main advantage of PVT collectors are to increase solar cell efficiency by reducing the solar cell operating temperature when the fluid (water or air) is extracted the heat from back of the PVT collector. Second is that the cost of one unit of PVT is less than the cost of an equivalent of thermal and photovoltaic panels. This is expected to qualify a lower production cost per kWh of annual produced hybrid energy. And third is that reduced installation area, which permits more installation capacity per roof area or lower installation costs. The photovoltaic thermal (PVT) systems came from theory into practical to utilize the thermal energy along with the electricity from the sun energy. The available thermal energy by PVT can be utilized for low potential works such as water and air heating. Further, the hot water or air can be used for various applications such as space heating, solar dryers, greenhouse and solar stills [1-3].

Solar based water collectors (water heater) are utilized to heat the water for various domestic and industrial purpose. The domestic solar water heater generally uses FPC in parallel connection for lager amount of water and runs automatically by the thermo-siphon action, whereas the water heater for industry purpose uses series connections of N number of collectors for higher outlet temperature but the thermo-siphon action does not work in this case and hence it works by electric water pump which is driven by a photovoltaic (PV), to maintain a flow of water inside the collector due to large length. For this operation, electrical energy is needed to drive the electrical motor to flow the water, which can be obtained by PV module [4]. Further, some researchers integrate the PVT concept with concentration to further increase the output thermal energy due to respective input energy through larger aperture. Concentrator also achieves higher temperatures that will reduce the efficiency of the solar cells in PVT collectors.

The relations between energy and exergy, energy and sustainable development, exergy and the environment in detail are reported [5]. Fudholi et al. [6] have studied the energy performance of a PVT water collector at range of 400–800 W/m^2 solar radiation. They observed that the maximum overall efficiency of PVT water collector is 68.4%, thermal efficiency is 52% and PV efficiency is 13 % at a solar radiation level of 800 W/m^2 and mass flow rate of 0.041 kg/s.

A thermal efficiency of more than 80% and an electrical efficiency enhancement of more than 20% can be obtained through the use of diffuse reflectors together with water cooling. More than 50% increase in thermal efficiency can be achieved by laminating the PV cells directly on the thermal absorber, with simultaneous enhancement of electrical efficiency due to reduced thermal resistance and improved heat transfer. Rejeb et al. [7] established and experimentally validated a mathematical model to analyze a parametric study for the fully covered tube single PVT collector. Aste et al. [8] reviewed PVT flat plate water collectors. They reviewed about each component of system like covered glass, thermal absorbers, PV area or material, different mass flow rate, and thermal insulation of the PVT water collectors. Their review reported that partially covered by semitransparent PV modules flat plate collector series connected was not studied experimentally in previous research. Therefore series connected partially covered PVT collectors have been studied experimentally in this study.

Sinha and Tiwari [9] studied the thermal performance of commercial solar hot water system for constant delivery temperatures. It was stated that the time taken for process decreases when constant delivery temperature increases. In same application, another approach was adopted [10]. Here, an exergy analysis of solar water heater for constant collection temperature and the results were also likened with constant flow rate operation. It was observed that the overall daily thermal efficiency of integrated photovoltaic thermal system (IPVTS) increased with the increase in constant mass flow rate and decreased with increase of constant collection temperature. Mishra and Tiwari [11] analyzed energy and exergy of hybrid photovoltaic thermal water collector for constant collection temperature mode. It was studied that hybrid PVT water collector for constant collection temperature mode has been performed by two different cases: [case (i) (partially covered PVT)] and [case (ii) (fully covered PVT)]. They have reported that case (i) is best suitable for thermal gain and case (ii) is best for electrical gain.

Deepali et al. [4] discussed exergy of photovoltaic thermal (PVT) compound parabolic concentrator (CPC) for constant collection temperature mode. They have compared two operation modes: constant flow mode and constant collection mode with four cases. It was also reported that fully covered PVT-CPC water collector is best for electrical gain whereas CPC collector has found best for thermal gain.

Zhang et al. [12] discussed the annual energy performance, CO_2 emission and mitigation, economic analysis on energy production and environmental benefits for cold (London), warm (Shanghai) and hot (Hong Kong) areas location. It was reported that the installing of any PVT system at any location depend upon mainly three factors namely energy efficiency, economic cost and environmental advantages. Tripathi et al. [13-15] studied the model for N identical photovoltaic thermal-compound parabolic concentrator collector. They concluded the partially covered N PVT-CPC collector was found to be best for thermal need and fully covered PVT-CPC collector for electrical need. Further, Tripathi and Tiwari [16, 17] compared four PVT family system including N PVT-CPC collector and found that N PVT-CPC collector is most suitable for the need of thermal as well as electrical point of view. They also investigated that single fully covered PVT-CPC collector and validated the theoretical and experimental results value by considering two different cases. Here, manual maximum power point tracking was found to be dominated by fixed position of collector.

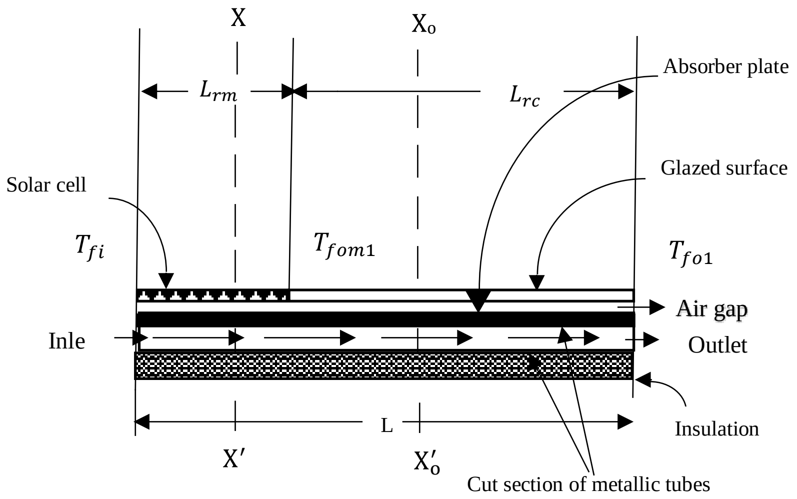
Generally, the hot fluid collection with constant temperature is required in industrial applications where constant temperature is needed for manufacturing process. To accept this requirement, an effort has been made to study the exergoeconomic analysis and estimation of earned carbon credits of N PVT-CPC collector with ethylene glycol for much higher temperature by considering the two different cases, namely: N-PVT-CPC collector [case (i)] and N-CPC collector [case (ii)] at constant outlet temperature mode for New Delhi, India in present paper.

Organization of the present paper: After present section, Introduction, there are five sections like: Section 2: system description, Section 3: thermal modeling or theory, Section 4: methodology, Section 5: results as well as descriptions and in the last Section 6: conclusions or outcomes.

II. SYSTEM DESCRIPTION

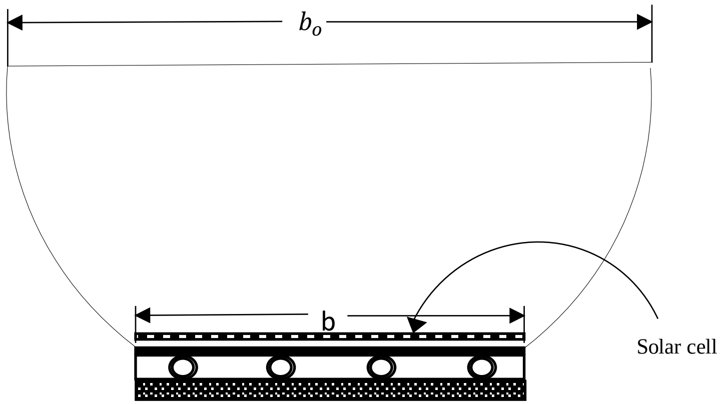
Tripathi et al. (2016 a) proposed the design of N partially covered PVT-CPC collector connected in series. The cross section view and front view of first collector of partially covered N- PVT-CPC water collector have been shown in Figs. 1(a) and 1(b) respectively.

Figure 1 (a):



Cross section side view of partially covered First of N- PVT-CPC collector and N-PVT collector, where A_r=1 m^2, A_{rm}=0.25 m^2 and A_{rc}=0.75 m^2 (25% PV coverage).

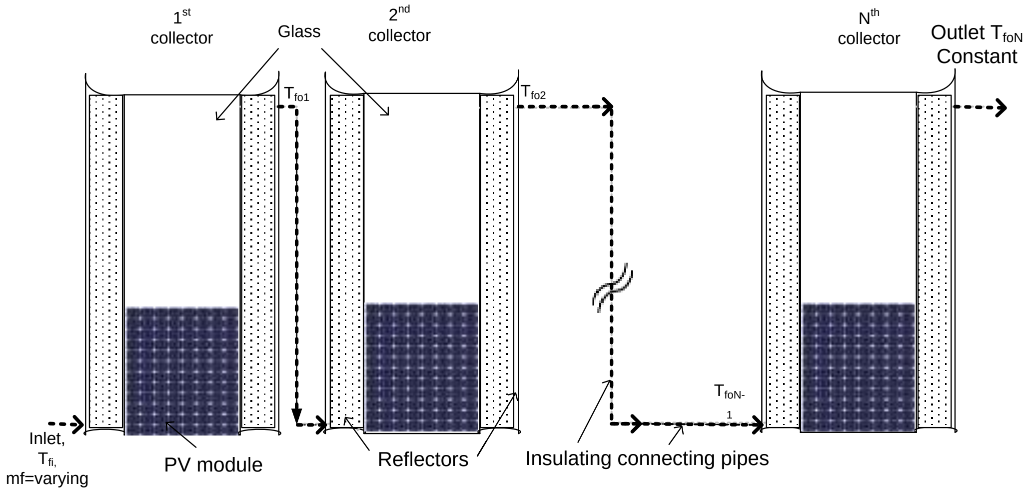
Figure 1 (b):



Cut section XX' front view of partially covered of First of N-PVT-CPC collector [case (i)], where A_a= 2m^2 (concentration ratio=2:1).

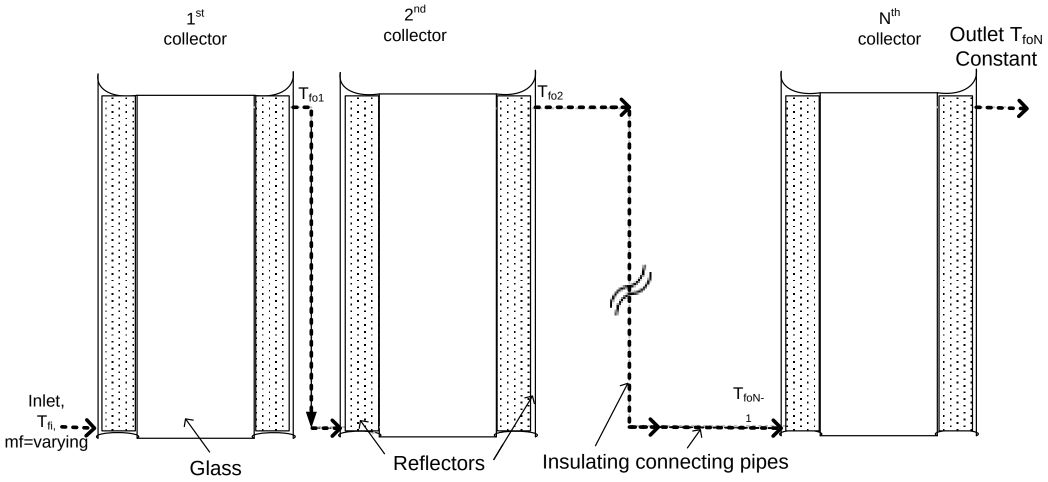
Here, the number of collectors are connected in series to increase the outlet temperature of fluid at N^th collector of the system. Schematic view of N-PVT-CPC [case (i)] and N-convectional compound parabolic concentrator (N-CPC) [case (ii)] collectors. Both are having effective receiver area of 1m² connected in series have been shown in Figs. 2 and 3, respectively.

Figure2:



Case (i): Series connected partially covered N Photovoltaic thermal (PVT) - compound parabolic concentrator (CPC) collectors [case (i)].

Figure 3:



Case (ii): Series connected N-Convectional compound parabolic concentrator (CPC) collector ($A_{am}=A_{rm}=A_m=0$).

Water as a fluid has been considered for N-PVT-CPC collectors at constant flow rate, earlier. But it has some limitations that it has upper limit of temperature about 100 ^{0}C which cannot be used for either steam cooking or power generation. Further, ethylene glycol has been chosen for achieving high outlet temperature in the present study. It has major advantages that it does not freeze at low temperatures so it is safe to use in colder weather whereas water does not corrode pipes and stops clogging and another advantage is that it is anti-corrosion. These two properties increase the life cycle of the system and utility of the system which is not possible in case of water as a fluid; because water has not anti-corrosion property. These makes this fluid popular in solar energy field. Wide operating temperature range (-10 ^{0}C to 190 ^{0}C) and low specific heat capacity of ethylene glycol encourages the uses in solar applications. Due to lower specific heat capacity of ethylene glycol, higher temperature can be achieved which is not possible in case of water. Hence it has been made an attempt to analyze the N-PVT-CPC collectors and N-CPC collector connected in series at constant outlet temperature mode to optimize the various parameters namely mass flow rate for a given outlet temperature and collector area with the same fluid. The design parameters of N identical PVT-CPC collectors and N-CPC collector at constant outlet temperature are given in Table 1.

Table 1. Values of design parameters of N-PVT-CPC [case (i)] and N-CPC collector [case (ii)].

A_r = 1 m^2	$U_{tc,p}$ = 5.58 W/m^2 °C
A_{rm} = 0.25 m^2	$U_{tp,a}$ = 4.8 W/m^2 °C
A_{rc} = 0.75 m^2	PF_1 = 0.3782
A_a = 2 m^2	PF_2 = 0.9512
A_{am} = 0.5 m^2	PF_c = 0.9842
A_{ac} = 1.5 m^2	h_{pf} = 100 W/m^2
c_f = 4179 J/kg K for water c_f = 2850 J/kg K for ethylene glycol	h_i = 5.7 W/m^2
T$_{cc}$= 150 ^{0}C	$h_i{}'$ = 5.8 W/m^2
F_{rm} = 0.8110 m^2	h_o = 9.5 W/m^2
K_g = 0.816 W/m °C L_g = 0.003 m	ρ = 0.84 τ_g = 0.95
K_i = 0.166W/m°C, L_i = 0.100 m	α_c = 0.9 β_c = 0.89
K_p = 6 W/m °C, L_p = 0.002 m	α_p = 0.8 F' = 0.9680
U_{L1} = 3.47 W/m^2 °C	F_{rc} = 0.8693 m^2
$U_{L,m}$ = 7.87 W/m^2 °C	FF =0.8
$U_{tc,a}$ = 9.17 W/m^2 °C	η_o = 0.15
U_{Lc} = 4.7 W/m^2 °C	Tube diameter = 0.0125 m

III. THERMAL MODELLING

Case (i): Photovoltaic thermal-compound parabolic concentrator (PVT-CPC)

Energy balance equation for solar cell of semitransparent PV module (Figs. 1a and 1b)

$$\rho\alpha_c\tau_g\beta_c I_b A_{am} = \left[U_{tc,a}(T_c - T_a) + U_{tc,p}(T_c - T_p)\right]A_{rm} + \rho\eta_m I_b A_{am} \tag{1}$$

From Eq. (1), one can find solar cell temperature (T_c) as follows:

$$T_c = \frac{(\alpha\tau)_{1,eff} I_b + U_{tc,a}T_a + U_{tc,p}T_p}{U_{tc,a} + U_{tc,p}} \tag{2}$$

Energy balance for absorber plate below the Photovoltaic module

$$\rho\alpha_p\tau_g^2\,(1 - \beta_c)I_b A_{am} + U_{t,cp}(T_c - T_p)A_{rm} = F'h_{pf}(T_p - T_f)A_{rm} + U_{t,pa}(T_p - T_f)A_{rm} \tag{3}$$

From Eq. (2) and (3), one can get an expression for as

$$T_p = \frac{[(\alpha\tau)_{2,eff} + PF_1\,(\alpha\tau)_{1,eff}]I_b + U_{L2}\,T_a + h_{pf}\,T_f}{(U_{L2} + h_{pf})} \tag{4}$$

Expressions for $(\alpha\tau)_{2,eff}$, $(\alpha\tau)_{1,eff}$, PF_1, U_{L2}, $h_{pf}, U_{tp,a}, U_{tc,a}$ and $U_{tc,p}$ have been given in appendix-A.

Energy balance for flowing water as fluid below the absorber plate

$$\dot{m}_f c_f \frac{dT_f}{dx} dx = F'h_{pf}(T_p - T_f)b\,dx \tag{5}$$

from Eqs. (2) and (4), Eq. (5) can be rewritten as follows:

$$\dot{m}_f c_f \frac{dT_f}{dx} dx = bF'[I_b PF_2(\alpha\tau)_{m,eff} - U_{l,m}(T_f - T_a)]dx \tag{6}$$

where, F' is the collector efficiency factor.

The solution of the above equation can be obtained by using initial condition i.e. $(T_f|_{x=0} = T_{fi})$ as

$$T_f = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_b}{U_{L,m}} + T_a\right]\left[1 - exp\left\{\frac{-bF'U_{L,m}x}{\dot{m}_f c_f}\right\}\right] + T_{fi}\,exp\left[\frac{-bF'U_{L,m}x}{\dot{m}_f c_f}\right] \tag{7}$$

The outlet water (as fluid) temperature at end of PV module can be evaluated as

$$T_{fom1} = T_f|_{x=L_{rm}} = \left[\frac{PF_2(\alpha\tau)_{m,eff} I_b}{U_{L,m}} + T_a\right]\left[1 - exp\left\{\frac{-F'U_{L,m}A_{Rm}}{\dot{m}_f c_f}\right\}\right] + T_{fi}\,exp\left[\frac{-F'U_{L,m}A_{Rm}}{\dot{m}_f c_f}\right] \tag{8}$$

After knowing T_{fom1} from Eq. 8, the outlet water temperature of first PVT-CPC collector T_{fo1} is given by

$$T_{fo1} = \frac{I_b\,(A\,F_R\,(\alpha\tau))_1}{\dot{m}_f C_f}\frac{(1-K_k{}^1)}{(1-K_k)} + \frac{T_a\;(A\,F_R U_L)_1}{\dot{m}_f C_f}\frac{(1-K_k{}^1)}{(1-K_k)} + T_{fi}\left(1-\frac{(A\,F_R U_L)_1}{\dot{m}_f C_f}\right) \tag{9}$$

The expression for T_{foN} and T_{fomN} in the present case has been obtained and one can get the following

$$T_{fomN} = \frac{I_b(A\,F_R\,(\alpha\tau))_{mN}}{\dot{m}_f C_f} + \frac{T_a(A\,F_R U_L)_1}{\dot{m}_f C_f} + T_{foN-1}\,K_m \tag{10}$$

$$T_{foN} = \frac{I_b(A\,F_R\,(\alpha\tau))_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} + \frac{T_a(A\,F_R U_L)_1}{\dot{m}_f C_f}\frac{(1-K_k{}^N)}{(1-K_k)} + T_{fi}\,K_k^N \tag{11}$$

Expressions for $(A\,F_R U_L)_1$, $(A\,F_R\,(\alpha\tau))_1$ and K_k have been given in appendix-A

Here, T_{foN} is considered as constant throughout the operation then $T_{foN}=T_{cc}$=constant. After calculating the final outlet fluid temperature at Nth collector, one can derived the mass flow rate at Nth collector of PVT-CPC system connected in series, following as

$$\dot{m}_f = \frac{I_b\left(AF_R\left(\alpha\tau\right)\right)_1 + T_a\left(AF_R U_L\right)_1}{C_f\left(T_{cc}-T_{fi}K_k^N\right)}\frac{\left(1-K_k^N\right)}{\left(1-K_k\right)} \tag{12}$$

where, T_{cc}= constant outlet temperature and expressions for $(A\,F_R U_L)_1$, $(A\,F_R\,(\alpha\tau))_1$ and K_k have been given in appendix-A.

Due to higher temperature collection throughout the year, the electrical efficiency decreases because open circuit voltage (V_{oc}) and the fill factor decrease whereas short-circuit current (I_{sc}) increases [18]. The total effect on temperature dependent electrical efficiency is given by the formula [19-21].

$$\eta_{cN} = \eta_0\left[1-\beta_0\left(\bar{T}_{cN}-T_0\right)\right] \tag{13}$$

where $\bar{T}_{cN}$ = average solar cell temperature of PV module.

It can be obtained from as following [13]

$$\eta_{cN} = \frac{\eta_0\left[1-\frac{\beta_0}{\left(U_{tc,p}+U_{tc,a}\right)}\left\{\left(XI_b+YT_a+ZT_{fi}\right)-T_0\right\}\right]}{\left[1-\frac{\eta_0\beta_0 I_b}{\left(U_{tc,p}+U_{tc,a}\right)}\left(\alpha+\beta\gamma\right)\right]} \tag{14}$$

where X, Y, Z, α, β and γ are defined in Appendix-A.

Case (ii): N-Convectional compound parabolic concentrator (N-CPC): at ($A_{am}=A_{rm}=A_m=0$).

Energy balance at absorber:

$$\rho\alpha_c\tau_g I_b A_{ac} = F' h_{pf}\left(T_p-T_f\right)A_{rc} + U_{t,pa}\left(T_p-T_a\right)A_{rc} \tag{15}$$

Energy balance for flowing fluid:

$$\dot{m}_f c_f \frac{dT_f}{dx}dx = F' h_{pf}\left(T_p-T_f\right)bdx \tag{16}$$

The solution of above Eq. (15) and (16) with initial condition $T_f=T_{fi}$ at x=0, is given as

$$T_f = \left[\frac{PF_c\left(\alpha\tau\right)_{c,eff}\,I_b}{U_{l,c}} + T_a\right]\left[1-\exp\left\{\frac{-F'U_{l,c}bx}{\dot{m}_f c_f}\right\}\right] + T_{fi}\exp\left\{\frac{-F'U_{l,c}bx}{\dot{m}_f c_f}\right\} \tag{17}$$

The outlet fluid temperature at the end of first collector is given as $T_f=T_{fo1}$ at $x=L_c$

$$T_{fo1} = \left[\frac{PF_c\left(\alpha\tau\right)_{c,eff}\,I_b}{U_{l,c}} + T_a\right]\left[1-\exp\left\{\frac{-F'U_{l,c}bL_c}{\dot{m}_f c_f}\right\}\right] + T_{fi}\exp\left\{\frac{-F'U_{l,c}bL_c}{\dot{m}_f c_f}\right\}$$

or

$$T_{fo1} = \left[\frac{PF_c\left(\alpha\tau\right)_{c,eff}\,I_b}{U_{l,c}} + T_a\right]\left[1-\exp\left\{\frac{-F'U_{l,c}A_{rc}}{\dot{m}_f c_f}\right\}\right] + T_{fi}\exp\left\{\frac{-F'U_{l,c}A_{rc}}{\dot{m}_f c_f}\right\} \tag{18}$$

where, A_{rc}=area of glazed receiver.

Further, in this case, N conventional CPC are connected in series, then expression for outlet fluid temperature at Nth collector will be found similar way as Eq. (11) with following condition as follows:

$$T_{foN}=I_b\left[\left(AF_R(\alpha\tau)\right)_1^{'}\frac{\left(1-K_k^{'(N)}\right)}{\left(1-K_k^{'}\right)}\right]+T_a\left[\frac{\left(AF_RU_L\right)_1^{'}}{\dot{m}_fc_f}\frac{\left(1-K_k^{'(N)}\right)}{\left(1-K_k^{'}\right)}\right]+T_{fi}K_k^{'(N)} \tag{19}$$

After calculating the final outlet fluid temperature at Nth collector, one can derive the mass flow rate at Nth collector of CPC collector connected in series, following as

$$\dot{m}_f=\frac{I_b\left(AF_R(\alpha\tau)\right)_1^{'}+T_a\left(AF_RU_L\right)_1^{'}}{C_f\left(T_{cc}-T_{fi}K_k^{'(N)}\right)}\frac{\left(1-K_k^{'(N)}\right)}{\left(1-K'_k\right)} \tag{20}$$

By using the same iteration method for mass flow rate, **the outlet temperature (T_{cc})** can be kept constant at Nth collector of PVT-CPC and CPC systems.

The rate of available thermal energy and useful thermal exergy at Nth collector of PVT-CPC and CPC systems, connected in series can be evaluated for each cases by using Eqs. (11), (12), (19) and (20), as follows:

$$\dot{E}_{eth,N}=\dot{m}_fc_f\left(T_{cc}-T_{fi}\right) \tag{21}$$

$$\dot{E}_{xth,N}=\dot{m}_fc_f\left(T_{cc}-T_{fi}\right)-\dot{m}_fc_f\left(T_a+273\right)ln\frac{(T_{cc}+273)}{(T_{fi}+273)} \tag{22}$$

where $\dot{m}_f$= mass flow rate of fluid, c_f= specific heat of fluid, T_{fi}= inlet fluid temperature and T_a= ambient air temperature.

Now, the temperature dependent electrical efficiency of PV modules for N-PVT-CPC collector [case (i)] has been obtained by using following expression as [13]

$$\eta_{mN}=\tau_g\beta_c\eta_{cN} \tag{23}$$

where η_{mN} is electrical efficiency of N- number of PV modules on N collectors.

Further, the rate of useful electrical gain for N-PVT-CPC collector [case (i)] from Nth collectors can be evaluated as:

$$\dot{E}_{ele,N}=A_{rm}I_b\sum_1^N\eta_{mN} \tag{24}$$

With help of Eqs. (21) and (24), the rate of an overall thermal energy gain for each cases has been evaluated from the following expression:

$$\sum\dot{Q}_{ue,overall,N}=\sum\dot{E}_{eth,N}+\sum\frac{\dot{E}_{ele,N}}{\gamma} \tag{25}$$

where γ= 0.38 is conversion factor from thermal to electrical power for best coal based thermal power plant. Since electrical power can be considered as equivalent to exergy gain by second law of thermodynamics and hence an overall exergy of the proposed system can be calculated for both cases from Eqs. (22) and (24), as follows:

$$\sum\dot{Q}_{uex,overall,N}=\sum\dot{E}_{xth,N}+\sum\dot{E}_{ele,N} \tag{26}$$

Exergoeconomic (cost to energy) analysis

Exergoeconomic analysis is analytical method of economics on exergy gain. It participates in exergy analysis with respect to cost factor to enhance the performance of systems. The aim of this process is to find ways how to enhance the performance of a system in a cost effectiveness. Exergoeconomic analysis has been adopted to evaluate cost effectiveness by reducing the loss of the systems or increase the gain of the system [22, 23]. Some researchers and scientists have reported the exergoeconomic parameter as the ratio of exergy loss to the net capital investment cost. Their motive was to reduce the loss in the system and they have focused on loss terms. But here, an attempt has been considered to analysis the same process by considering gain [23]. Hence, exergoeconomic parameter on the basis of exergy gain with an aim to maximize the exergy gain for proposed system has been adopted for the comparison. Now, the exergoeconomic parameter (R_{ex}) for N-PVT-CPC collector can be written as

$$R_{ex,N}=\frac{\dot{Q}_{uex,overall,N}}{UAC_{,N}} \tag{27}$$

where $\dot{Q}_{uex,overall,N}$ and UAC$_N$ are annual exergy gain and uniform end-of-year annual cost for both cases respectively.

The calculation of uniform end-of-year annual cost (UAC) is based on the present value method. Table 2 represents the capital investment of the proposed system for both cases. The salvage value has been calculated

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based on the current price of different materials of the system in Indian local market. The uniform end-of-year annual cost for a given initial investment of both cases can be expressed as [3 and 23-24]

$$UAC_{,N} = (P_s * F_{CR,i,n}) + (M * F_{CR,i,n}) - (S_s * F_{SR,i,n}) \tag{28}$$

where P_s, S_s and M are the net present cost, salvage value and maintenance cost of the both systems respectively. Capital investment (P_s) of both systems has been calculated in Table 2.

Table 2. Capital investment for producing the proposed systems.

S. No.	**Systems**	**N-PVT-CPC [case (i)]**	**N-CPC [case (ii)]**
1.	Cost of one collector (Rs.)	10500	9250
2.	No. of collector (N=6)	63000	55500
3.	Cost of connecting pipes (copper) (Rs.)	200	200
4.	Cost of insulation of connecting pipes (Rs.)	1600	1600
5.	Transportation cost (Rs.)	1000	1000
	Total (P_s in Rs.)	**65800**	**58300**

The maintenance cost (M) has been taken as 10% of present value (P_s) of the system. Hence, the maintenance cost can be taken as $M=0.10*P_s$. F_{CR},i,n and F_{SR},i,n are capital recovery factor and sinking fund factor respectively. F_{CR},i,n and F_{SR},i,n can be obtained by expression following as:

$$F_{CR,i,n} = \frac{i(1+i)^n}{(1+i)^n - 1} \tag{29}$$

and

$$F_{SR,i,n} = \frac{i}{(1+i)^n - 1} \tag{30}$$

where i and n are the rate of interest and life of the system, respectively.
The exergoeconomic parameters for both cases (i-ii) have been calculated using Eq. (27) and presented in Table 3.

Table 3. Uniform annual cost (UAC) of capital investment, annual exergy gain and exergetic cost of partially covered N-photovoltaic thermal (PVT-CPC) collector [case (i)] and N- conventional compound parabolic concentrator (N-CPC) collector [case (ii)] for 30 and 50 year.

i (frac.)	**n (yrs)**	**P_s (Rs.) [case (i)]**	**P_s (Rs.) [case (ii)]**	**F_{cr}**	**F_{sr}**	**S (Rs.) (@i= 0.04) [case (i)]**	**S (Rs.) (@i= 0.04) [case (ii)]**	**M (Rs.) (@10%*P_s) [case (i)]**	**M (Rs.) (@10%*P_s) [case (ii)]**
0.02	30	65800	58300	0.044	0.024	21341	18909	6580	5830
0.05	30	65800	58300	0.065	0.015	21341	18909	6580	5830
0.1	30	65800	58300	0.106	0.006	21341	18909	6580	5830
0.02	50	65800	58300	0.031	0.011	46761	41431	6580	5830
0.05	50	65800	58300	0.054	0.004	46761	41431	6580	5830
0.1	50	65800	58300	0.100	0.0008	46761	41431	6580	5830

Table 3 Continued ….

$UAC_{,N}$ (Rs.) [case (i)]	**$UAC_{,N}$ (Rs.) [case (ii)]**	**E_{ex} (kWh) [case (i)]**	**E_{ex} (kWh) [case (ii)]**	**R_{ex} (kWh/Rs) [case (i)]**	**R_{ex} (kWh/Rs) [case (ii)]**
2705.69	2397.29	98.42	130.6	0.036	0.054
4387.20	3887.14	98.42	130.6	0.022	0.033
7548.27	6687.90	98.42	130.6	0.013	0.019
1750.48	1550.96	98.42	130.6	0.056	0.084
3741.37	3314.92	98.42	130.6	0.026	0.039

7260.01	6432.50	98.42	130.6	0.013	0.020

Enviroeconomic (carbon mitigation and credits) analysis

The enviroeconomic study is carried upon rate of CO_2 emission into the environment, which supports the renewable energy techniques that doesn't emit carbon particles to the atmosphere. This approach has been taken to calculate CO_2 mitigation or reduction of CO_2 emission into atmosphere for life cycle. The enviroeconomic analysis describes environmental benefits by generating energy or exergy from any system or calculates the carbon mitigation, while a carbon credits is a financial tool that is equivalent to one ton of carbon dioxide emission. Credits are awarded to countries or groups that have reduced their greenhouse gases or CO_2 below their emission levels. Carbon credits can be legally traded in the international market at their current market price.

For electricity generation from coal in the power plant, the average CO_2 emits in environment is 980 $gmCO_2/kWh$ approximately [25]. However transmission losses are 40% and distribution losses are 20%, due to the disorganized transmission system and inefficient electrical equipments, which are considered in power supply. Then the total CO_2 per kWh comes to be 2.08 kg. Therefore, CO_2 mitigation in tons per annum from partially covered N-PVT-CPC water collectors is given as

$$\o_{CO_2} = \frac{\psi_{CO_2} \times \dot{Q}_{u,overall,N}}{10^3} \tag{31}$$

where ψ_{CO_2} is the average CO_2 emission for power production by coal (2.08 $kgCO_2/kW$ h), $\o_{CO_2}$ is CO_2 mitigation per annum (tCO_2/annum), and $\dot{Q}_{u,overall}$ is the annual overall thermal energy ($\dot{Q}_{ue,overall,N}$) and exergy gain ($\dot{Q}_{uex,overall,N}$) from partially covered N-PVT-CPC collector and N-CPC collector per annum.

The range of CO_2 price is from13 $\$/tCO_2$ to 16 $\$/tCO_2$ for international market [26]. The average value of CO_2 14.5 $\$/tCO_2$ has been adopted for numerical computation or analysis of environmental cost [27-31], which is given as

$$Z_{CO_2} = P_{CO_2} \times \o_{CO_2} \tag{32}$$

where Z_{CO_2} is the enviroeconomic cost or carbon credits (CO_2 mitigation price per annum) ($/annum) and P_{CO_2} is the carbon price per tCO_2 (average price has been taken as 14.5 $\$/tCO_2$).

The numerical computation of enviroeconomic analysis has given in Table 4.

Table 4. CO_2 mitigation and carbon credits of partially covered N-PVT-CPC collector [case (i)] and N-CPC collector [case (ii)] on the basis of annual energy and exergy gain for 30 and 50 year.

Systems	**Gain/year**		**CO_2 emission per unit by customer (in Kg/kWh)**	**CO_2 mitigation in $kgCO_2$/year**		**CO_2 mitigation in tCO_2/year**	
	Energy (kWh)	**Exergy (kWh)**		**Energy (E)**	**Exergy (Ex)**	**Energy (E)**	**Exergy (Ex)**
N-PVT-CPC **[case (i)]**	514.63	98.42	2.04	1049.84	200.77	1.049	0.200
N-CPC **[case (ii)]**	758.79	130.6	2.04	1547.93	266.42	1.547	0.266

n (years)	**CO_2 mitigation (tones CO_2)**		**CO_2 mitigation price ($)**	**CO_2 mitigation ($/$tCO_2e$)**		**$ (cost in Rs.)**	**Carbon credits (Rs. /tCO_2e)**	
	Energy (E)	**Exergy (Ex)**		**Energy (E)**	**Exergy (Ex)**		**Energy (E)**	**Exergy (Ex)**
30	31.49	6.02	14.5	456.68	87.33	67.28	30725	5876
30	46.43	7.99	14.5	673.35	115.89	67.28	45303	7797

Table 4 Continued ….

Table 4 Continued ….

n (yrs)	CO2 emission (tCO_2/n)		Co_2 mitigation (in $)	Co_2 mitigation ($/tCO2e)		$ (cost in Rs.)	Carbon credits (Rs. /tCO_2e)	
	Energy (E)	Exergy (Ex)		Energy (E)	Exergy (Ex)		Energy (E)	Exergy (Ex)
50	52.49	10.03	14.5	761.13	145.56	67.28	51209	9793
50	77.39	13.32	14.5	1122.2	193.15	67.28	75505	12995

IV. METHODOLOGY

The hourly data of total radiation, beam radiation on horizontal surface and ambient air temperature have been obtained from India Meteorological Department (IMD), Pune, India. Further, total radiation, beam radiation have been calculated at 30° (latitude) inclination for New Delhi, India by using MATLAB 2013a to enhance the gain of the system and the result has been shown in Fig.4. The design parameters have been given in Table 1.

The following methodologies have been adopted:

(i) Through basic energy balance equations, the outlet fluid temperature of Nth collector (T_{foN}) for N-PVT-CPC and CPC systems connected in series have been derived in Eqs. (11) and (19). After getting (T_{foN}), to keep constant the outlet temperature ($T_{foN}=T_{CC}$=constant), the mass flow rate ($\dot{m}_f$) at N^{th} collector of PVT-CPC collectors [case (i)] and N-CPC collectors [case (ii)] have been derived in Eqs. (12) and (20), respectively. The value of mass flow rate of fluid has been obtained by iteration method. The results has been shown in Figs. 5 and 7 (a) and hourly results for both cases have been shown in Fig. 7 (b).

(ii) The temperature dependent electrical efficiency of PV cells (η_{cN}) at N^{th} collectors of N-PVT-CPC collectors [case (i)] has been evaluated from Eq. (14) and the results have been shown in Fig. 6.

(iii) After getting $\dot{m}_f$ for hourly for cases (i-ii) by iteration method, the rate of available thermal energy and useful thermal exergy have been evaluated by using Eqs. (21) and (22), respectively and hourly results have been shown in Figs. 8.

(iv) By Eq. (14), [η_{cN} for {case (i)}], an electrical efficiency of PV module (η_{mN}) has been evaluated from Eq. (23). The electrical gain for cases have been evaluated from Eq. (24) and the results have been shown in Fig.9.

(v) Hourly overall thermal and exergy for each cases have been evaluated from Eqs. (25) and (26), respectively which have been shown in Figs.10.

(vi) Daily thermal energy, thermal exergy, electrical gain, overall thermal energy and overall exergy have been calculated by summing the hourly rate of useful thermal energy, thermal exergy, electrical gain, overall thermal energy and overall exergy for both cases.

(vii) Monthly thermal energy, thermal exergy, electrical gain, overall thermal energy and overall exergy have been calculated by multiplying the daily thermal exergy electrical gain, overall thermal energy and overall exergy with number of clear days in every month for both cases.

(viii) Annual electrical gain, overall thermal energy and overall exergy have been calculated by summing the all monthly gain of electrical gain, overall thermal energy and overall exergy for both cases.

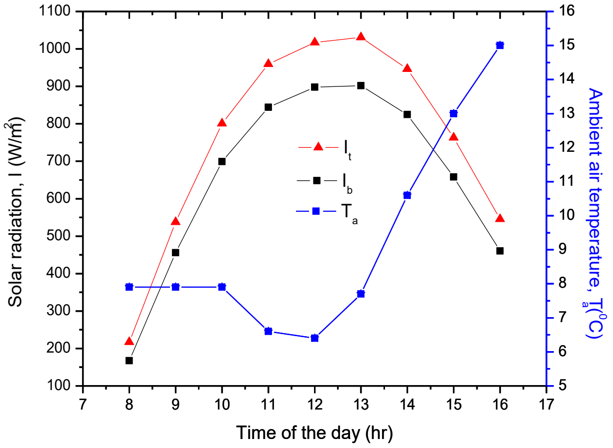
(ix) After obtaining annual exergy of both cases, the exergoeconomic parameter has been calculated by Eq. (27) through Eqs. (28), (29) and (30). The values of R_{ex} for exergy gain of cases (i-ii) (N-PVT-CPC and N-CPC collectors) have been calculated in Table 3.

(x) Enviroeconomic analysis has been performed on the basis of energy and exergy gain for cases (i-ii) (N-PVT-CPC and N-CPC collectors) by Eq. (32) through (31). The environmental cost for systems have been placed in Table 4.

V. RESULTS AND DISCUSSION

Hourly variation of total and beam radiation and ambient air temperature for a clear sky condition for a typical day of January at 30° latitude, New Delhi, India has been shown in Fig. 4. Hourly variation of mass flow rate of N-PVT-CPC [case (i)] has been shown for water and ethylene glycol considering as working fluid at constant outlet temperature (100 ^{0}C) in Fig. 5. It is seen that higher value of mass flow rate has been taken for ethylene glycol to the water at the same constant temperature.

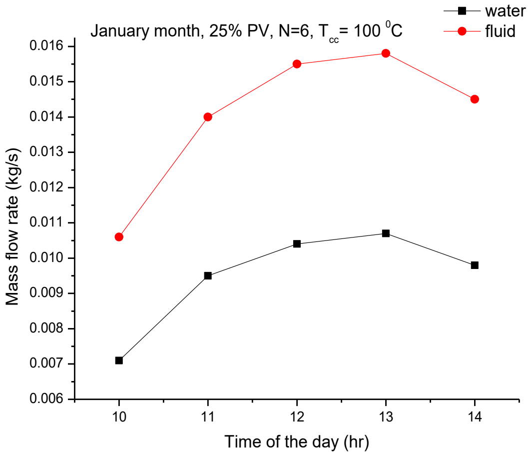
Figure 4:



Hourly variation of climatic parameters like total solar radiation, beam radiation and ambient air temperature of a clear day in month of January for New Delhi, India.

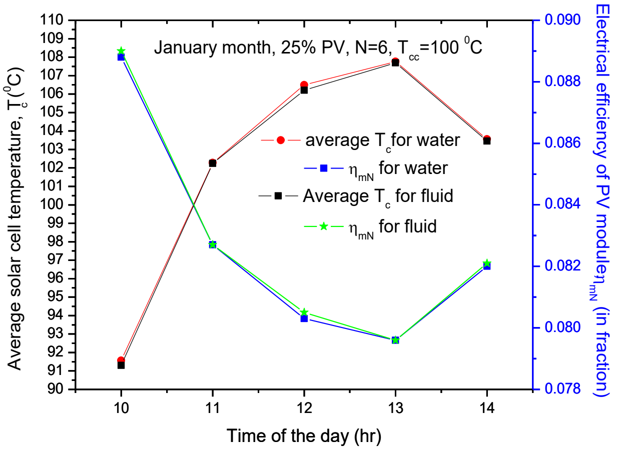
The hourly variation of average solar cell temperature and electrical efficiency of PV module of N-PVT-CPC [case (i)] has been shown for both fluids (water and ethylene glycol) at constant outlet temperature (100 ^{0}C) in Fig. 6. It is observed that the electrical efficiency of PV module decreases with increase in average solar cell temperature. Water has limitation that it cannot take more than 100 ^{0}C temperature at pressure 1.01 bar. For higher temperature, other fluid has been chosen which ethylene glycol is. It has -10 ^{0}C to 190 ^{0}C operating temperature.

Figure 5:



Hourly variation of mass flow rate of partially covered N-photovoltaic thermal (PVT) - compound parabolic concentrator (CPC) collector [case (i)] for two different fluid: water and ethylene glycol for a clear day condition.

Figure 6:



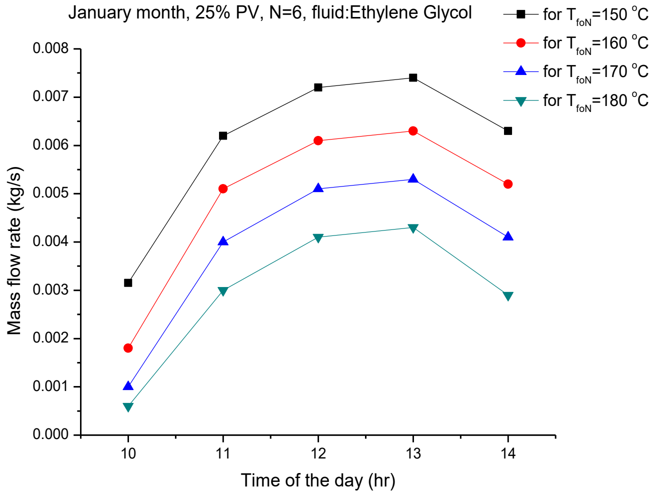
Hourly variation of average solar cell temperature to electrical efficiency of PV module of partially covered N-photovoltaic thermal (PVT) - compound parabolic concentrator (CPC) collector [case (i)] for two different fluid: water and ethylene glycol for a clear day condition.

Hourly variation of mass flow rates of N-PVT-CPC [case (i)] at different constant outlet temperatures has been shown in Fig. 7 (a). It is observed that mass flow rate of fluid decreases with increase in constant outlet temperature. The hourly variation of mass flow rate of ethylene glycol has been shown for N-PVT-CPC collector and N-CPC collector [case (i) and case (ii)] respectively, in Fig. 7 (b). It is seen that higher mass flow rate of ethylene glycol has been obtained at constant outlet temperature 150 ^{0}C for N-CPC [case (i)] to N-PVT-CPC [case (ii)].

The hourly variation of thermal energy and exergy for both cases have been shown at constant outlet temperature with working fluid as ethylene glycol in Figs. 8. It is found that higher thermal energy and exergy have been obtained in N-CPC collector [case (ii)] due to large area of glass.

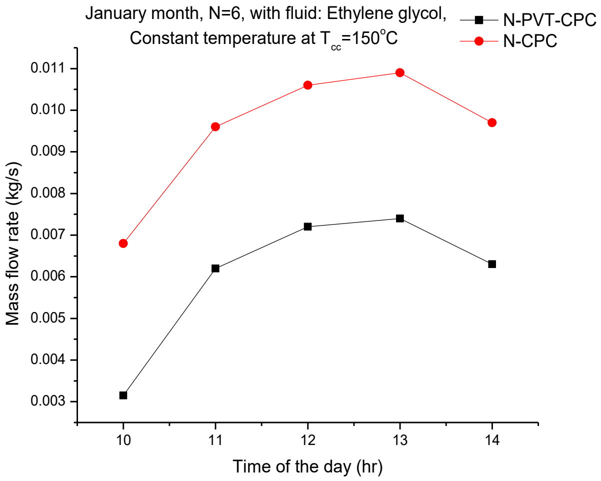
Hourly variation of electrical gain for N-PVT-CPC [case (i)] has been shown in Fig. 9. The daily electrical gain in month of January has been found 0.45 kWh in five number of hours in a day at 150 ^{0}C constant outlet temperature.

Figure 7 (a):



Hourly variation of different mass flow rate to different constant collection temperature for partially covered N-photovoltaic thermal (PVT) - compound parabolic concentrator (CPC) collector [case (i)] with fluid: ethylene glycol for a clear day condition.

Figure 7 (b):



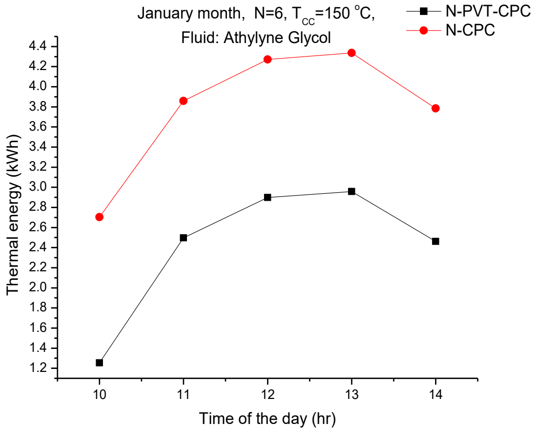
Hourly variation of mass flow rate at constant collection temperature (150 ^{0}C) for N-PVT-CPC collector [case (i)] and N- CPC collector [case (ii)] with fluid: ethylene glycol for a clear day condition.

Figs. 10 show the hourly variation of overall thermal energy and exergy of both cases with working fluid: ethylene glycol in month of January. It is observed that overall energy and exergy have been obtained maximum in N-CPC collector [case (ii)]. Fig. 11 shows the monthly variation of electrical gain of partially covered N-PVT-CPC [case (i)]. The maximum electrical gain has been obtained in month of September due to large number of clear days and minimum in month of July due to large cloudy days. The net electrical gain has been obtained 18.38 kWh per year.

Monthly variation of overall thermal energy gain and exergy have been shown in Figs. 12.

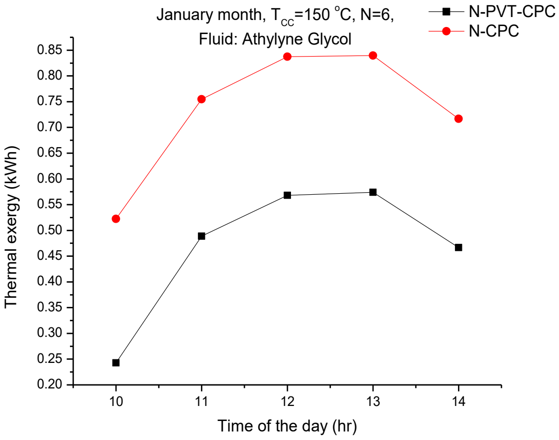
Overall thermal energy gain has been maximum for N-CPC [case (ii)] in every month and the net yearly overall thermal energy gain has been achieved as 758.79 kWh. The monthly overall exergy has been found maximum for N-CPC [case (ii)] in every month of the year. It is observed that the net overall exergy has been achieved in a year is 130.60 kWh per year for N-CPC [case (ii)].

Figure 8 (a):



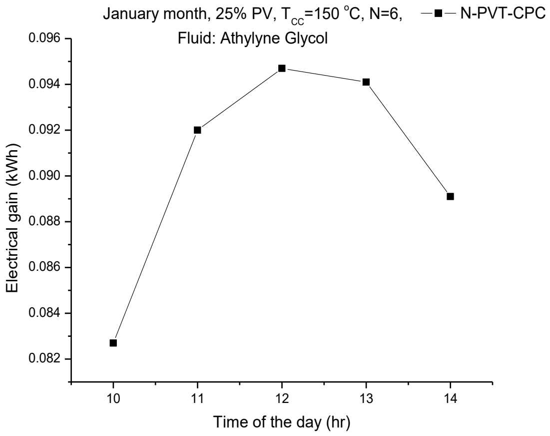
Hourly variation of thermal energy at constant collection temperature (150 ^{0}C) for N-PVT-CPC collector [case (i)] and N- CPC collector [case (ii)] with fluid: ethylene glycol for a clear day condition.

Figure 8 (b):



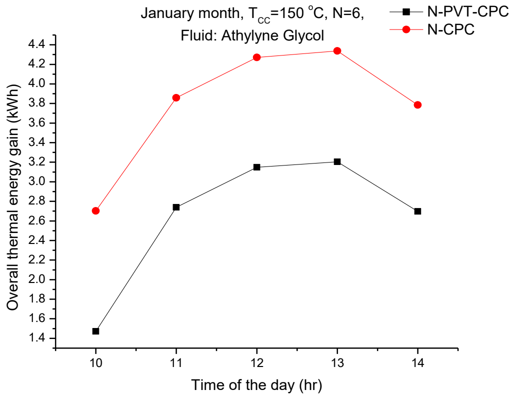
Hourly variation of thermal exergy at constant collection temperature (150 ^{0}C) for N-PVT-CPC collector [case (i)] and N- CPC collector [case (ii)] with fluid: ethylene glycol for a clear day condition.

Figure 9:



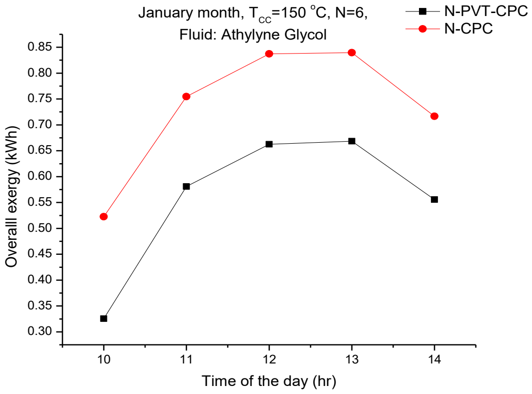
Hourly variation of electrical gain at constant collection temperature (150 ^{0}C) for N-PVT-CPC collector [case (i)] and N- CPC collector [case (ii)] with fluid: ethylene glycol, New Delhi, India.

Figure 10 (a):



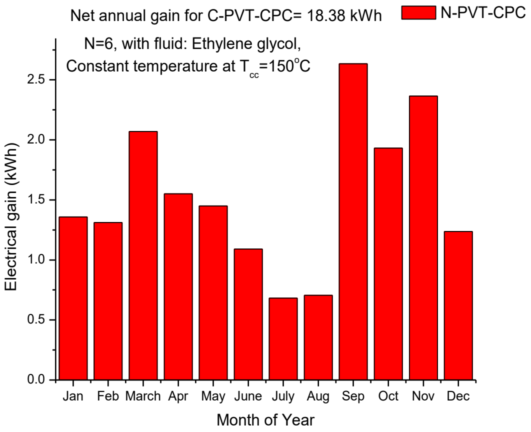
Hourly variation of overall thermal energy gain at constant collection temperature (150 ^{0}C) for N-PVT-CPC collector [case (i)] N- CPC collector [case (ii)] with fluid: ethylene glycol at New Delhi, India.

Figure 10 (b):



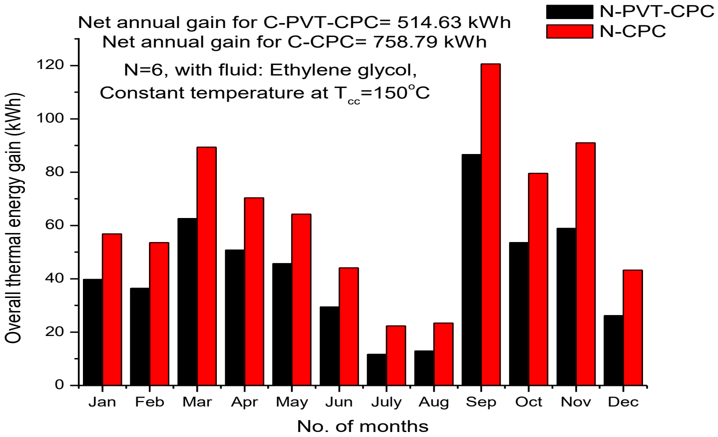
Hourly variation of overall exergy at constant collection temperature for N-PVT-CPC collector [case (i)] N- CPC collector [case (ii)] with fluid: ethylene glycol at New Delhi, India.

Figure 11:



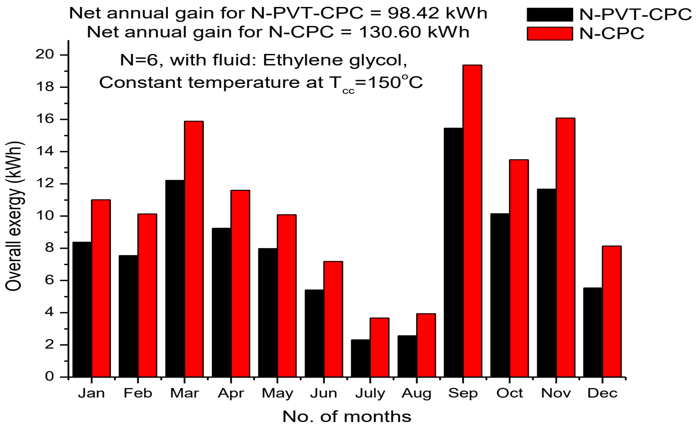
Monthly variation of electrical gain at constant collection temperature for N-PVT-CPC collector [case (i)] with fluid: ethylene glycol, New Delhi, India.

Figure 12 (a):



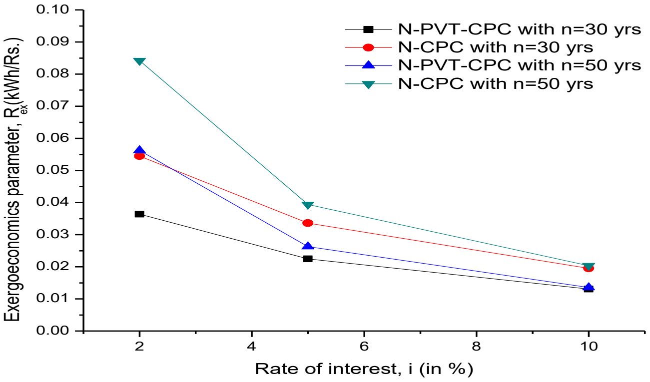
Monthly variation of overall thermal energy gain at constant collection temperature for N-PVT-CPC collector [case (i)] and N-CPC [case (ii)] with fluid: ethylene glycol, New Delhi, India.

Figure 12 (b):



Monthly variation of overall exergy at constant collection temperature for N-PVT-CPC collector [case (i)] and N-CPC [case (ii)] with fluid: ethylene glycol, New Delhi, India.

Figure 13:



Rate of interest variation of exergoeconomic parameters for N-PVT-CPC collector [case (i)] and N-CPC [case (ii)] with fluid: ethylene glycol for different number of years.

Fig. 13 shows the variation of rate of interest to exergoeconomic parameter R_{ex} for cases [(i)-(ii)]. It is observed that exergoeconomic parameter decreases with increase in rate of interest (i) for different number of years (n) due to increase in UAC by increase of rate of interest. The obtained exergoeconomic parameter (R_{ex}) is higher for N-CPC collector [case (ii)] to [case (i)] at same rate of interest (i) and number of years (n).

The exergoeconomic parameter with [n, i= 30, 0.02 and 50, 0.02] for N-CPC [case (ii)] is 1.5 times and 1.6 times respectively higher than N-PVT-CPC [case (i)]. For one year life cycle, CO_2 emission and mitigation have been found higher for N-CPC collector [case (ii)] due to higher energy and exergy gain. For 30 and 50 years life cycle, CO_2 emission or mitigation for N-CPC collector [case (ii)] has been calculated 1.4 and 1.5 times higher than N-PVT-CPC [case (i)].

VI. CONCLUSIONS

Certain conclusions have been prepared by the present study as followed:

- Partially covered N-PVT–CPC collectors connected in series [case (i)] with ethylene glycol as a working fluid has achieved higher mass flow rate at same constant outlet temperature to water as working fluid. It reflects that higher mass with same time can be obtained when working fluid is ethylene glycol.
- The net annual electrical gain has been achieved as 18.38 kWh for partially covered N-PVT-CPC collectors connected in series [case (i)] at constant outlet temperature whereas no electrical gain is in N-CPC collector connected in series [case (ii)] and it is not self-

sustainable due to absence of electrical energy (PV module). Whereas partially covered N-PVT-CPC collector connected in series overcome this drawback and it can be used for thermal as well as electrical energy need.

- The maximum net annual overall thermal energy and exergy have been obtained as 758.79 kWh and 130.60 kWh respectively, at constant outlet temperature (150 ^{0}C) for N-CPC collector connected in series with working fluid as ethylene glycol [case (ii)] which is 1.5 and 1.3 times higher than N-PVT-CPC collector [case (i)]. It can be concluded that N-CPC collector is more suitable than N-PVT-CPC collector for higher temperature at constant outlet mode operation.
- For life cycle (30 years), the exergoeconomic cost parameter for N-CPC collector [case (ii)] at 2% interest rate has found 50% higher than N-PVT-CPC [case (i)] and environmental cost (for exergy basis) for N-CPC collector [case (ii)] has found higher 32 % than N-PVT-CPC [case (i)].

VII. APPENDIX

Following mathematical terms are used in thermal modelling and study of partially covered N-PVT-CPC collectors and other systems:

$$U_{tc,a} = \left[\frac{1}{h_o} + \frac{L_g}{K_g}\right]^{-1}; \qquad U_{tc,p} = \left[\frac{1}{h_i} + \frac{L_g}{K_g}\right]^{-1};$$

$$h_o = 5.7 + 3.8V, W/m^2K; \quad V = 1\,m/s\ ;\ h_i = 5.7\ W/m^2K;$$

$$U_{tp,a} = \left[\frac{1}{U_{tc,a}} + \frac{1}{U_{tc,p}}\right]^{-1} + \left[\frac{1}{h_i'} + \frac{1}{h_{pf}} + \frac{L_i}{K_i}\right]^{-1};$$

$$h_i' = 2.8 + 3V', W/m^2K; \ V' = 1\,m/s;$$

$$U_{L1} = \frac{U_{tc,p}U_{tc,a}}{U_{tc,p} + U_{tc,a}}; \ U_{L2} = U_{L1} + U_{tp,a};$$

$$U_{L,m} = \frac{h_{pf}U_{L2}}{F'h_{pf}+U_{L2}}\ ;\ U_{L,c} = \frac{h_{pf}U_{tp,a}}{F'h_{pf}+U_{tp,a}};$$

$$PF_1 = \frac{U_{tc,p}}{U_{tc,p}+U_{tc,a}}; \ PF_2 = \frac{h_{pf}}{F'h_{pf}+U_{L2}};$$

$$PF_c = \frac{h_{pf}}{F'h_{pf}+U_{tp,a}};$$

For case (i):

$$(\alpha\tau)_{1,eff} = \rho(\alpha_c - \eta_c)\tau_g\beta_c\frac{A_{am}}{A_{rm}}; \quad (\alpha\tau)_{2,eff} = \rho\alpha_p\tau_g{}^2(1-\beta)\frac{A_{am}}{A_{rm}};$$

$$(\alpha\tau)_{m,eff} = \left[(\alpha\tau)_{1,eff} + PF_1(\alpha\tau)_{1,eff}\right]; \ (\alpha\tau)_{c,eff} = PF_c\rho\alpha_p\tau_g\frac{A_{ac}}{A_{rc}};$$

$$A_{rm} = bL_{rm}; \ A_{am} = b_oL_{am};$$

$$A_cF_{Rc} = \frac{\dot{m}_fc_f}{U_{L,c}}\left[1 - exp\left(\frac{-F'U_{L,c}A_c}{\dot{m}_fc_f}\right)\right];$$

$$A_mF_{Rm} = \frac{\dot{m}_fc_f}{U_{L,m}}\left[1 - exp\left(\frac{-F'U_{L,m}A_m}{\dot{m}_fc_f}\right)\right];$$

$$\left(AF_R(\alpha\tau)\right)_1 = \left[A_cF_{Rc}(\alpha\tau)_{c,eff} + PF_2(\alpha\tau)_{m,eff}A_mF_{Rm}\left(1 - \frac{A_cF_{Rc}U_{L,c}}{\dot{m}_fc_f}\right)\right];$$

$$(AF_RU_L)_1 = \left[A_cF_{Rc}U_{L,c} + A_mF_{Rm}U_{L,m}\left(1 - \frac{A_cF_{Rc}U_{L,c}}{\dot{m}_fc_f}\right)\right];$$

$$K_k = \left(1 - \frac{(AF_RU_L)_1}{\dot{m}_fc_f}\right);$$

$$\left(AF_R(\alpha\tau)\right)_{m1} = PF_2(\alpha\tau)_{m,eff}A_mF_{Rm};$$

$$(AF_RU_L)_{m1} = A_mF_{Rm}U_{L,m}; \ K_m = \left(1 - \frac{A_mF_{Rm}U_{L,m}}{\dot{m}_fc_f}\right);$$

For case (ii):

$$(\alpha\tau)_{c,eff}{}' = PF_c\rho\alpha_p\tau_g\frac{A_{ac}}{A_{rc}};$$

$$\left(AF_R(\alpha\tau)\right)_1{}' = \left[A_cF_{Rc}(\alpha\tau)_{c,eff}{}'\right];$$

$$(AF_RU_L)_1{}' = \left[A_cF_{Rc}U_{L,c}\right];$$

$$A_cF_{Rc} = \frac{\dot{m}_fc_f}{U_{L,c}}\left[1 - exp\left(\frac{-F'U_{L,c}A_c}{\dot{m}_fc_f}\right)\right]$$

$$K_k{}' = \left(1 - \frac{(AF_R U_L)_1{}'}{\dot{m}_f c_f}\right);$$

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