Energetic and Exergetic Comparison of Photovoltaic Thermal (PVT) Arrays

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Abstract
The study presents the overall thermal energy and exergy analysis of three types of hybrid Photovoltaic Thermal (PVT) array which is a series parallel combination of 36 numbers of PV modules (10.08m x 2.16m). A comparison has been made between the three configurations, which are explained as, case-A: 2 integrated columns each having 18 opaque PV modules in series are connected in parallel, case-B: Two integrated columns of 18 modules each having 36 PVT tiles in the module is connected in series (area of each tile is 0.124m x 0.124m) and case-C: 2 integrated columns each having 18 semi-transparent PV modules in series are connected in parallel. A one-dimensional transient model for hybrid PVT array has been developed using basic heat transfer equations. The performance of the three cases has been compared on the basis of annual overall thermal energy and exergy gain for four different climatic conditions (Bangalore, Jodhpur, New Delhi, and Srinagar) of India. As compared with case-A and case-B, case-C has lower cell temperature (28.8% and 12.1%), higher electrical efficiency (9.9% and 3.1%) and higher average outlet air temperature (40.6% and 19.1%). In all the cases, the month of May yields the highest value of overall thermal energy gain and electrical energy gain. The overall annual thermal energy and exergy gain is highest for Bangalore among all cities and case-C yields the highest value of 5.24×104 kWh (higher by 15.3% and 5.0% from case-A and 2) and 2.44×104 kWh (higher by 17.3% and 7.3% from case-A and 2) respectively. As far as overall performance is considered, configuration under case-C offers a greater potential of energy saving as compared to the other two cases.

Keywords
Energy; Exergy; PVT array

I. Introduction

The current energy scenario is gradually shifting towards non conventional sources of energy and is going to be a main substitute for fossil fuels in the coming years for their clean and renewable nature.

Green [1] showed that the short circuit current of PV cells is not strongly temperature dependent; however it tends to increase slightly due to increased light absorption. He attributes this to the temperature dependant decrease in band gap in the semiconductor materials used in the cells. Bucher et al. [2] studied the factors responsible for the performance deviation of PV module from their rating at standard test condition (STC). Tripanagnostopoulos et al. [3] conducted tests on hybrid PVT systems using poly-crystalline (pc-Si) and amorphous silicon (a-Si) PV cells. They found that the cooling provided by the thermal integration assisted in improving the efficiency of the PV cells by approximately 10%. Additionally, they found that water cooling provided better cooling than air circulation.

Van Helden et al. [4] observed that 80% of the incident solar radiations are absorbed by PV collectors but only a small portion of this is converted to electrical energy and the remainder being dissipated as thermal energy. Coventry [5] has studied the performance of a concentrating PV/T collector and concluded that an overall thermal and electrical efficiency of concentrating PV/T system are 58% and 11%, respectively. This gives a total efficiency of the system as 69%. Tiwari et al. [6] have validated the theoretical and experimental results for PV module integrated with air duct for composite climate of India and concluded that an overall thermal efficiency of PV/T system is significantly increased (18%) due to utilization of thermal energy from PV module.

The possibility of generating electricity and heat energy from a commercial PV module adopted as a PVT air solar collector with either forced or natural airflow in the channel was demonstrated by Tonui and Tripanagnostopoulos [7]. A brief description of the theory and mechanism of building integrated photovoltaic thermal (BIPVT) systems has been presented by Ibrahim et al. [8]. Abdolzadeh and Ameri [9] have investigated the possibility of improving the performance of a photovoltaic water pumping system by spraying water over the front of PV array experimentally. They have pointed out that the efficiency of PV array can be increased due to spraying water over the front of PV array. Dubey and Tiwari [10] have made a detailed analysis of thermal energy, exergy and electrical energy yield by varying the number of collectors by considering four weather conditions. Candanedo et al. [11] compared their general steady state and transient PVT air collector models with experimental data from an experimental facility at Concordia University. Chen et al. [12] investigated a BIPVT system thermally coupled with a ventilated concrete slab in a low energy solar house located in the cold climate of Quebec. A typical thermal efficiency of 20% for the BIPVT system was reported. Agrawal and Tiwari [13] have presented the concept of series and parallel connections of micro-channel solar cell thermal tiles to analyze overall energy and exergy of hybrid micro-channel PVT module. Agrawal and Tiwari [14] have studied on different configurations of glazed micro-channel solar cell thermal tiles and they validated the results of a single tile. Efficient single glazed flat plate PVT hybrid collector for domestic hot water system has been studied by Dupeyrat et al. [15] and they found that direct lamination of sc-Si PV cells on an optimized metal heat exchanger leads to the best results among the other investigated concepts. Norton et al. [16] have given the concept of enhancing the performance of building integrated photovoltaics. They reviewed the building integrated photovoltaic (BIPV) system on the basis of some key systems which includes invertors, concentrators and thermal management systems. Vats and Tiwari [17] derived the analytical expression for room air temperature of building integrated semitransparent photovoltaic thermal (BISPVT) and building integrated opaque photovoltaic thermal (BIOPVT) systems each integrated to the roof of a room with and without air duct. Bambrook and Sproul [18] illustrated the influence of fundamental parameter values on the thermal performance of the PVT collector. Vats and Tiwari [19] carried out a comparative study to evaluate the energy and exergy performance of a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated to the roof of a room considering six different photovoltaic (PV) modules. They have concluded that HIT PV module is suitable for producing electrical power whereas a-Si is suitable for space heating.

In this paper, energetic and exergetic analysis has been carried out for different hybrid PVT arrays. The results of the present study (considered as case-C) are compared with the optimum case of the study carried out by Rajoria et al. [20, 21] (considered as case-A and case-B) and some important deductions have been made. Same cities as considered in the study conducted by Rajoria et al [20] have been considered to cater for the different climatic conditions of India. Further, these cities are classified under four different climatic condition of India (Bansal and Minke, [22]), namely 'Type a (clear days)', 'Type b (hazy days)', 'Type c (hazy and cloudy days)' and 'Type d (cloudy days)'. The energy and exergy gain for different climatic conditions of India has been evaluated and on the basis of these gains, the CO2 mitigation (tCO2/annum) and enviroeconomic (environmental cost) parameter ($/annum) has been evaluated and compared.

II. System Specifications

The optimum configuration of Rajoria et al. [20, 21] has been considered as case-A and case-B in the present study. In case-C, 2 integrated columns each having 18 semi-transparent PV modules in series are connected in parallel has been considered as shown in fig. 1.

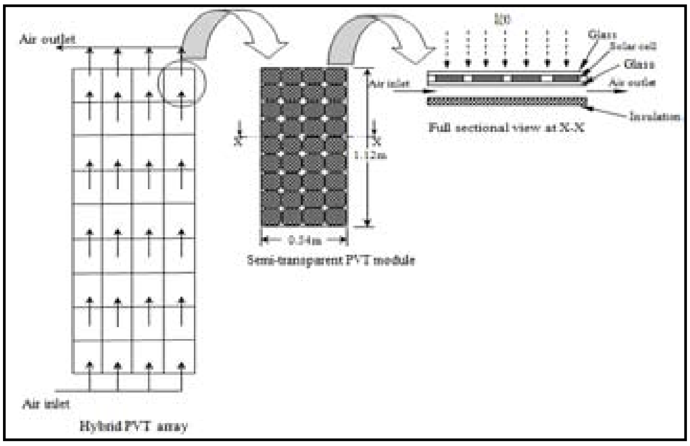

Fig. 1: Typical Layout of a Hybrid PVT array showing a typical flow configuration with an enlarged view of a semi-transparent PV module and its full sectional view

III. Thermal Modeling and Analysis

In order to write the energy balance equation of PV modules, the same assumptions and methodology have been considered as in Rajoria et al [20]:

A. For semi-transparent PVT Module

The energy balance equation for semi-transparent PVT module can be written as

$$\alpha_c\tau_g\beta_c I(t)b.dx=\left[U_{tc,a}\left(T_c-T_a\right)+U_{tc,f}\left(T_c-T_f\right)\right]b.dx+\alpha_c\tau_g\beta_c\eta I(t)b.dx \quad (1)$$

Where, b is the width of the PVT tile and dx is the elemental length in the direction of flow of air.

From Eq. (1), the expression for solar cell temperature is

$$T_c=\frac{\alpha_{eff}I(t)+U_{tc,a}T_a+U_{tc,f}T_f}{U_{tc,a}+U_{tc,f}} \quad (2)$$

Where, $\alpha_{eff}=\alpha_c\tau_g\beta_c(1-\eta)$

The expression for temperature dependent electrical efficiency of a PVT tile can be written as.

$\eta=\eta_o[1-\beta_o(T_c-T_a)]$, Evans [23] and Schott [24] (3)

B. For the air flowing in the duct:

$$\left[\tau_g^2(1-\beta_c)I(t)+U_{tc,f}\left(T_c-T_f\right)\right]b\,dx=\dot m_f C_f\left(\frac{dT_f}{dx}\right)dx+U_{bs,r}\left(T_f-T_r\right)b\,dx \quad (4)$$

On simplifying Eq. (4) we get

$$\frac{dT_f}{dx}+\frac{bU_{L'}}{\dot m_f C_f}T_f=\left[U_{bs,r}T_r+U_{tl}T_a+\left(\tau_g^2(1-\beta_c)+h_p\alpha_{eff}\right)I(t)\right]\frac{b}{\dot m_f C_f} \quad (5)$$

Eq. (5) can be written in the following form

$$\frac{dT_f}{dx}+aT_f=f(x) \quad (6)$$

Where,

$$a=\frac{bU_L}{\dot m_f C_f}$$

$$f(x)=\left[h_{p1}h_p\alpha_{eff}I(t)+U_L T_a\right]\frac{b}{\dot m_f C_f}$$

The solution of Eq. (6) is obtained by integrating and applying initial conditions at x=0, $T_f=T_{fi}$; at x=L, $T_f=T_{fo}$

$$T_f=\frac{f(x)}{a}(1-\exp(-ax))+T_{fi}\exp(-ax) \quad (7)$$

and

$$T_{fo}=\frac{f(x)}{a}(1-\exp(-aL))+T_{fi}\exp(-aL) \quad (8)$$

Following Eq. (8), the outlet air temperature from Nth PVT module connected in series is derived as,

$$T_{foN}=\left[\frac{U_{bs,r}T_r+U_{tl}T_a+\left(\tau_g^2(1-\beta_c)+h_p\alpha_{eff}\right)I(t)}{U_{L'}}\right]\left(1-e^{-\frac{NbU_L L}{\dot m_f C_f}}\right)+T_r e^{-\frac{NbU_L L}{\dot m_f C_f}} \quad (9)$$

1. Useful heat gain or overall thermal energy gain

If all sets of hybrid PVT tiles modules are identical, then the expression for useful heat gain for n_{pv} row of PVT module and N_{pv} row of hybrid PVT array is given as

$$\dot Q_{u,(n_{pv}N_{pv})}=n_{pv}N_{pv}\dot m_f C_f(T_{fonN}-T_{fi}) \quad (10)$$

Substituting value of T_{fonN} from Eq. (9) in Eq. (10) we have

$$\dot Q_u=n_{pv}N_{pv}\dot m_f C_f\left[\frac{U_{bs,r}T_r+U_{tl}T_a+\left(\tau_g^2(1-\beta_c)+h_p\alpha_{eff}\right)I(t)}{U_{L'}}-T_r\right]\left(1-e^{-\frac{NbU_L L}{\dot m_f C_f}}\right) \quad (11)$$

The electrical energy gain (kWh), of hybrid PVT array is given as

$$\dot{Ex}_{electrical}=\left[\frac{\eta.N.A_c.I(t)}{1000}\right] \quad (12)$$

The overall thermal energy gain (kWh), is obtained using the following expression

$$\sum \dot{Q}_{u,overall} = \sum \dot{Q}_{u,(n_{pv}N_{pv})} + \sum \frac{\dot{E}x_{electrical}}{\eta_{cpower}} \qquad (13)$$

The factor η_{cpower} is known as electric power generation efficiency conversion factor of a conventional power plant which varies from 0.20-0.40 for a conventional power plant, Huang et al. [25]. The value depends upon the quality of coal, since India has poor quality coal; this value is taken as 0.38.

2. Overall Exergy Gain

The temperature difference between the outlet air and the atmospheric air leads to the transformation of thermal energy into work. This transformation is associated with irreversibilities, which restricts the complete conversion of thermal energy into work. The extent of transformability of thermal energy into work is governed by Carnot efficiency, therefore the thermal exergy gain is

$$\dot{E}x_{thermal} = \dot{Q}_{u,(n_{pv}N_{pv})}\left[1 - \frac{T_a + 273}{T_{fonN} + 273}\right] \qquad (14)$$

The overall exergy gain (kWh) from hybrid PVT array is obtained by summing up the electrical energy gain and the thermal exergy gain

$$\sum \dot{E}x_{overall} = \sum \dot{E}x_{electrical} + \sum \dot{E}x_{thermal} \qquad (15)$$

IV. Methodology

The same climatic data regarding solar radiation and ambient temperature has been used as in Rajoria et al. [20].

The annual overall thermal energy and exergy gain are obtained as follows:

A. Annual Overall Thermal Energy Gain

1. For the configuration explained in system description, the hourly rate of useful thermal energy gain is computed using Eq. (11) considering N = 18, n_{pv} =1 and N_{pv} = 2.
2. By summing hourly rate of useful thermal energy gain, the daily thermal gain has been calculated followed by calculation of monthly thermal energy gain by multiplying daily thermal gain and number of clear days in a month.
3. Annual thermal energy gain has been calculated by summing the monthly thermal energy gain.
4. The annual overall thermal energy gain has been calculated using Eq. (13).

B. Annual Overall Exergy Gain

1. For configurations explained in system description, the hourly electrical energy gain is computed using Eq. (12) considering N = 36.
2. By summing the hourly rate of electrical energy gain, the daily electrical energy gain has been calculated followed by calculation of monthly electrical energy gain by multiplying daily electrical energy gain and number of clear days in a month.
3. Annual electrical energy gain has been calculated by summing the monthly electrical energy gain.
4. The annual overall exergy gain has been calculated using Eq. (15).

V. Results and Discussion

The value of various design parameters in the hybrid PVT array has been given in Table 1. To compute the various data MATLAB7 has been used.

Table 1: Design Parameters of Hybrid PVT Array

Parameters	Values
A_c	0.0144 m^2
b	0.12 m
C_f	1005 J/kg K
hp	0.375
$hp1$	0.965
h_T	10.3 W/m^2 K
K_g	1.1 W/m K
K_T	0.033 W/m K
L	0.12 m
L_g	0.003 m
L_T	0.003 m
$\dot{m}_f$	0.0112 kg/sec
U_b	0.62 W/m^2K
U_T	66 W/m^2K
U_L	5.62 W/m^2K
$U_{tc,a}$	11.4 W/m^2K
α_c	0.9
β_c	0.83
η_o	0.12
τ_g	0.95
α_T	0.5

The hourly variations of cell temperature and cell efficiency for the climatic condition of Delhi in the month of January have been shown in fig. 2. It has been observed that the cell temperature in case-C is lower by 28.0% & 12.0% as compared to those observed in case-A & B respectively and therefore, the electrical efficiency in case-C comes higher than case-A & B. This is due to better heat removal in case-B which is attributed to better air circulation in the system. The average electrical efficiency in case-C is 9.9% & 3.1% higher than case-A & B respectively. Fig.3 shows the hourly variations of outlet air temperature for the climatic condition of Delhi in the month of January.

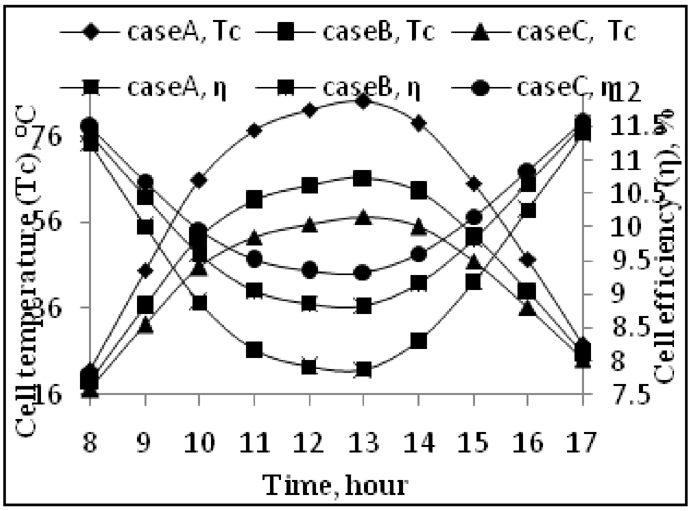

Fig. 2: Hourly Variations of Cell Temperature and Cell Efficiency for Delhi Climatic Condition in the Month of January

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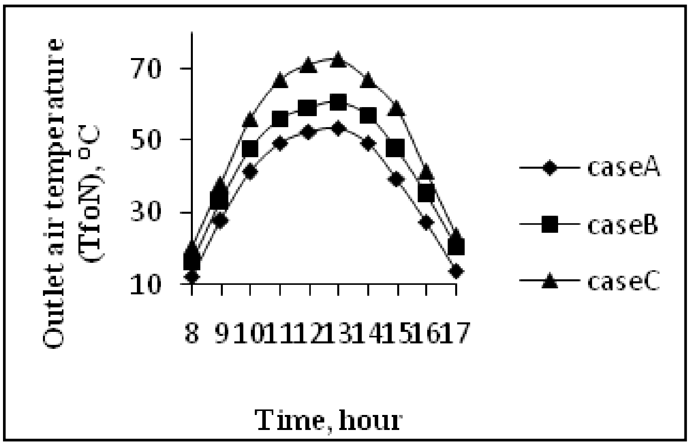

Fig. 3: Hourly Variations of Outlet Air Temperature for Delhi Climatic Condition in the Month of January

The outlet air temperature values for case-C are on higher side compared to case-A due to better design in the former case which gives a higher retention time for the air to carry away the heat from the system. The average outlet air temperature is 18.1% higher in case-C as compared to case-A & B.

The monthly variations of electrical energy gain considering a – d type weather condition for the climatic condition of Delhi has been depicted in fig. 4.

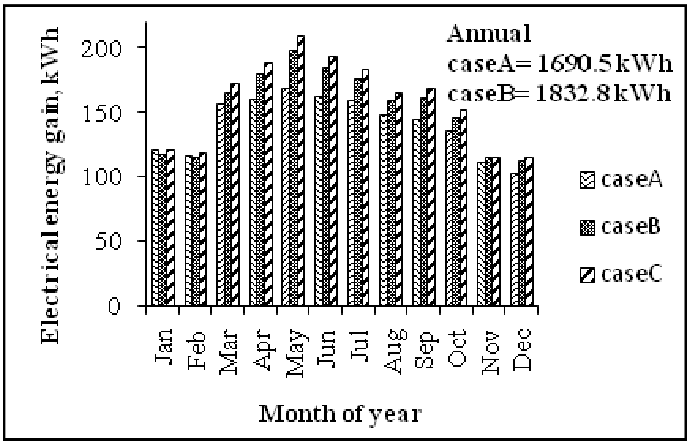

Fig. 4: Monthly Variations of Electrical Energy Gain Considering a – d Type Weather Condition for Delhi Climatic Condition

It is interesting to note that in the month of May, for case-C, the relative electrical energy gain is 17.4% higher than case-A followed by June (13.3%). This is due to higher solar intensity in these months.

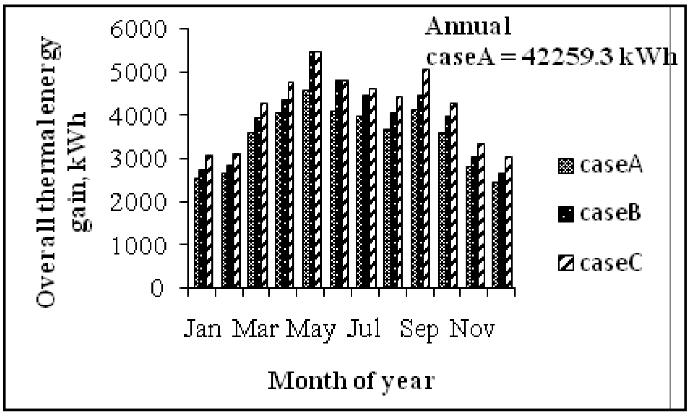

Fig. 5: Monthly Variations of Overall Thermal Energy Gain by combining a-d type weather conditions of a hybrid PVT array for Delhi

The values of annual electrical energy gain for case-A and case-C are 1690.5 kWh and 1832.8 kWh respectively. Also, the annual electrical gain in case-C exceeds by 8.4%. The monthly variations of overall thermal energy gain by combining a-d type weather conditions of a hybrid PVT array for Delhi has been shown in fig. 5.

It is important to observe that overall thermal energy gain for each month, in case-C is higher than case-A and also, the relative overall thermal energy gain for case-C in the month of May is higher by 20.5% against case-A followed by 17.7% for June. The values of annual overall thermal energy gain for case-A and case-C are 42259.3 kWh and 47026.6 kWh respectively and also, the annual overall thermal gain for case-C is higher by 11.3%. Since, the air passes through each PVT tile as explained in system description, the higher value of overall thermal energy gain is attributed to higher heat extraction capability of the system complimented by high solar intensity and more number of clear days. Fig. 6. shows the monthly variations of overall exergy gain by combining a-d type weather conditions of a hybrid PVT array for Delhi.

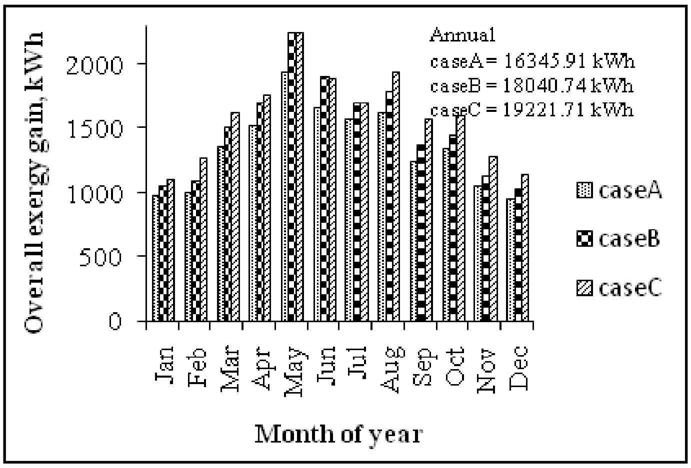

Fig. 6: Monthly variations of overall exergy gain by combining a-d type weather conditions of a hybrid PVT array for Delhi

It has been observed that, the exergy gain for case-C is highest in the month of May (2248.05 kWh) which is 15.5% higher than case-A & B followed by June (14.3%). The values of annual overall exergy gain for case-A and case-C are 16345.91 kWh and 18040.74 kWh respectively. Also, the annual overall exergy gain for case-C is higher by 10.4%. The higher values correspond to availability of more number of clear days and higher solar intensity. The annual overall thermal energy and exergy gain for four different cities of India by considering a–d type weather condition of hybrid PVT array has been shown in figs. 7 and 8 respectively.

Similar to the trend in case-A, the highest value of annual thermal energy and exergy gain for case-B have been observed for the climatic condition of Bangalore (49903.54 kWh and 22720.25 kWh respectively) which is higher from case-A & B by 9.9% and 9.4% respectively, this trend is observed due to availability of more number of clear days and moderately high values of solar intensity and moderate temperature. The annual overall thermal energy and exergy gain for case-B is observed to be the highest for the climatic condition of Delhi (11.3%) and Srinagar (16.3%) among all the cities discussed, therefore, it can be concluded that Delhi offers a greater opportunity for the system when thermal gain is considered and when electrical gain is considered, Srinagar offers a greater opportunity.

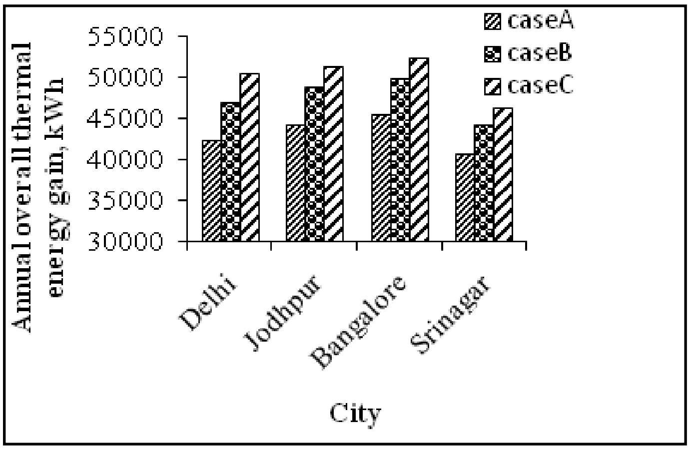

Fig. 7. Annual overall thermal energy gain for four different cities of India by considering a–d type weather condition of hybrid PVT array

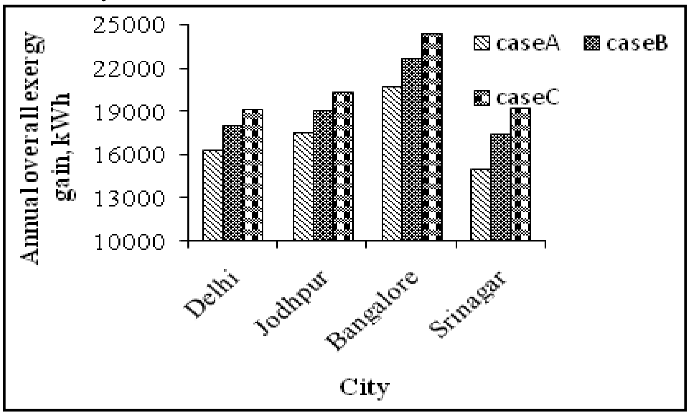

Fig. 8. Annual overall exergy gain for four different cities of India by considering a–d type weather condition of hybrid PVT array

VI. Conclusion

Energetic and exergetic analysis of the present system has been done and its performance has been compared with the study conducted by Rajoria et al. (2012). The following conclusions have been drawn.

As compared with case-A and case-B, Case-C has:

1. Lower cell temperature (28.8% and 12.1%).
2. Higher electrical efficiency (9.9% and 3.1%).
3. Higher average outlet air temperature (40.6% and 19.1%).

The overall annual thermal energy and exergy gain is highest for Bangalore among all cities and case-C yields the highest value of 5.24×104 kWh (higher by 15.3% and 5.0% from case-A and B) and 2.44×104 kWh (higher by 17.3% and 7.3% from case-A and B)

In comparison to case-B, the annual overall thermal energy gain under case-C for Delhi, Jodhpur, Bangalore & Srinagar exceeds by 7.1%, 5.0%, 4.9% and 5.0% respectively and the annual overall exergy gain exceeds by 6.5%, 6.8%, 7.3% and 9.9% respectively. Therefore, case-C is suitable for Delhi in terms of overall thermal energy and suitable for Jodhpur, Bangalore and Srinagar in terms of overall exergy.

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