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A newer approach on cash flow diagram to investigate the effect of energy payback time and earned carbon credits on life cycle cost of different photovoltaic thermal array systems

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Abstract

In this paper, three types of configurations have been considered namely (i) opaque type PVT array (case A) (ii) solar cell tile (SCT) array (case B) and (iii) semitransparent array (case C). The performances of all above cases have been computed using three basic metrics. These are the energy payback time (EPBT), the energy production factor (EPF) and the life cycle conversion efficiency (LCCE). When effect of EPBT is considered in the cash flow of the PVT array system, the annualized uniform cost has increased by 7.0% for lowest value and 16.5% for highest value on both energy and exergy basis. The values reflected this approach is more realistic than the conventional approach. While considering the effect of carbon credits earned and EPBT on annualized uniform cost of the PVT array system, the higher value of annualized uniform cost is indicative of better and efficient system which has the capability to compensate the cost incurred in the system. It has also been observed that among all the cases, case-C is a better performer in terms of energy and exergy.

Keywords: Energy payback time; Exergy; PVT array; Annualized uniform cost

1. Introduction

Photovoltaic energy conversion is considered as one of the most promising renewable energy technology which has the potential to contribute significantly to a sustainable energy supply and to mitigate greenhouse gas emissions. The world depends upon fossil fuels for its energy needs. However, the obligation to reduce CO_2 and other gas emissions in order to be in conformity with the Kyoto agreement is the reason behind which countries turn to non-polluting renewable energy sources.

Developments in the design and manufacture of PV cells have been very rapid over the last few years because they are now predicted to become a major renewable energy source. The embodied energy payback is important factor for renewable technologies as their use makes no sense if the energy used in their manufacturing is more than they can save in their life-time. The embodied energy payback period should always be one of the main criterions used for comparing the viability of one renewable technology against another.

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Nomenclature

A	area of semi-transparent PVT module, m^2
b	width of semi-transparent PVT module, m
C_f	specific heat of air, J/kg K
dx	elemental length, m
$\dot{E}x$	exergy, kW h
h_i	heat transfer coefficient from solar cell to flowing air, W/m^2 K
$h_{p'}$	penalty factor for top surface of PVT array
$I(t)$	incident solar intensity, W/m^2
L	length, m
$\dot{m}_f$	mass flow rate of air in PVT array, kg/s
n_{pv}	number of rows of PVT array
N	number of PVT air collectors
$\dot{Q}_u$	useful heat, W
T	temperature, K
$\bar{T}$	average temperature, K
U_b	overall back loss coefficient from flowing water to ambient, W/m^2 °C
$U_{L'}$	overall heat transfer coefficient for the system, W/m^2 °C
$U_{tc,a}$	overall heat transfer coefficient from solar cell to ambient through glass cover, W/m^2 °C
$U_{tc,f}$	overall heat transfer coefficient from solar cell to flowing fluid through bottom glass cover, W/m^2 °C

Subscripts

a	ambient
c	solar cell
eff	effective
f	fluid (air)
f_i	inlet fluid
f_o	outgoing fluid
g	glass
m	module

Greek letters

α	absorptivity
β_c	packing factor
β_o	temperature coefficient of efficiency, K^{-1}
$\phi(t)$	life cycle conversion efficiency
χ_a	energy production factor
η_c	temperature dependent solar cell efficiency
η_o	efficiency at standard test condition ($I(t) = 1000$ W/m^2, $T_a = 25$ °C)
τ	transmissivity

Abbreviations

CRF	capital recovery factor
EPBT	energy payback time
EPF	energy production factor
LCCE	life cycle conversion efficiency
PVT	photovoltaic thermal
SCT	solar cell tile
tCO_2e	tons of CO_2 equivalent

At first, the energy analysis of a PV module has been done by Slesser and Hounam (1976) and it has been reported that the energy payback time (EPBT) of a PV module is 40 years. Here, the EPBT of a PV module is defined as; "the ratio of energy consumed to produce the PV system to the annual energy generated from the PV system by using solar energy". A similar study has been conducted by Hunt (1977) and a value of 12 years of energy payback time for a PV module was obtained. The result reported by Hunt (1977) has also in general agreement with those of Kato et al. (1998) for crystalline silicon (c-Si) solar cell module.

Aulich et al. (1986) have evaluated the EPBT for a crystalline silicon module and it has been concluded that the EPBT is 8 years; in this case plastic materials have been used for encapsulation for Siemens crystalline process. The EPBT for a crystalline silicon (c-Si) solar cell module under Indian climatic condition for annual peak load duration is about four years (Prakash and Bansal, 1995). Alsema and Nieuwlaar (2000) have attempted to forecast the EPBT for a mono-crystalline solar cell for the year 2020, taking into account the improved technology and the efficiency of the solar cell; it has been concluded that the present EPBT, which is 5–6 years, gets reduced to 1.5–2 years.

Keolein and Lewis (1997) have predicted the EPBT for an amorphous silicon (a-Si) solar cell module with efficiency of 5% as 7.4 years for the climatic conditions of Detroit, USA; the EPBT gets reduced to 4.1 years with the increase in the efficiency of the module to 9%. Srinivas et al. (1992) have reported that the EPBT for an amorphous silicon (a-Si) solar cell module reduces to 2.6 years after considering gross energy requirement (GER) and the hidden energy. Yamada et al. (1995) have evaluated the EPBT for both polycrystalline and an amorphous silicon solar cell and reported that the EPBT for these cells are 5.7 and 6.3 years, respectively at the annual power production rate of 0.01 GW/year.

Battisti and Corrado (2005) have investigated the EPBT for a conventional multi-crystalline building integrated system, retrofitted on a tilted roof, located in Rome (Italy) with the yearly global insolation on a horizontal plane has been taken as 1530 kW h/m^2 per year. They have concluded that the EPBT gets reduced from 3.3 years to 2.8 years. Based on the worldwide survey, Gaiddon and

Jedliczka (2006) have presented the comparative assessment of selected environmental indicators of photovoltaic electricity in OECD cities. They found that the EPBT of a complete PV system was in the range of 1.6 to 3.3 years for a roof-mounted system and from 2.7 to 4.7 years for a PV-façade and energy return factor (ERF) is between 8 and 18 for roof-mounted systems and between 5.4 and 10 for PV façades considering 30 years long commercial life cycle. They have also found that the one single kWp of PV panels can avoid up to 40 tons of carbon dioxide (CO_2) during its whole commercial life and 23.5 tons of CO_2 per kWp for PV façades.

Radhi (2010) has studied the impact of PV technology on EPBT estimation in UAE commercial buildings and showed that, for the southern and western facades in the UAE, the embodied energy pay-back time for photovoltaic system is within the range of 12–13 years. Chel and Tiwari (2011) have presented a rigorous experimental outdoor performance of a 2.32 kW_P stand-alone photovoltaic (SAPV) system in New Delhi (India) for four weather types. They experimentally found that the daily power generated from the existing SAPV system was the range of 4–6 kW h/day depending on the prevailing sky conditions.

The earlier researches on the computation of energy metrics of PV systems were further extended to PVT technology which has and added advantage of producing thermal energy along with electrical energy and that too with enhanced module efficiency. Due to the higher overall output form a PVT system the EPBT significantly reduces and the EPF and LCCE of the PVT system increases. Tiwari et al. (2009) have performed the energy analysis of a PVT air collector on the basis of overall thermal energy and exergy basis; their study revealed that the EPBT gets significantly reduced by taking into account the increase in annual energy availability of the thermal energy in addition to the electrical energy. The values of EPF and LCCE of PVT air collector also become higher as expected.

Agrawal et al. (2012) have given the design and indoor experiment analysis of glazed hybrid photovoltaic thermal tiles air collector connected in series and concluded that if the numbers of glazed PVT tile are connected in series then it will be more beneficial from overall energy and overall exergy point of view. Mishra and Tiwari (2013) have evaluated and compared the energy metrics of a photovoltaic thermal (PVT) water collector under constant collection temperature mode with five different types of PV modules namely c-Si, p-Si, a-Si (thin film), CdTe and CIGS. They have observed that the maximum and minimum EPBT of 1.01 and 0.66 years is obtained for c-Si on energy basis and EPF and LCCE increase with increasing the life time of the system. The energy metrics of PVT air collector for on the basis of annual overall thermal energy and exergy for New Delhi has been carried out by Agrawal and Tiwari (2013) they have investigated that, by including the cost of energy in the manufacturing of components of the PVT module air collector, the payback/efficiency was increased/decreased respectively by roughly a factor of four.

Carbon credit trading (Emission Trading) is an administrative approach used to control the pollution by providing economic incentives for achieving reductions in the emissions of pollutants. A credit means, owner have a right to emit one ton of carbon dioxide equivalent (1 credit = 1 tCO_2e). International treaties such as the Kyoto protocol set quotas on the amount of greenhouse gases countries can produce. Energy consumption of a country is one of the indicators of its socio economic development. Per capita energy consumption in India is also one of the lowest in the world. It is about 30% of that in China, about 22% of that in Brazil and about 3.18% of that in the USA. With development, the per capita energy consumption is likely to increase.

At present, in India annual economic growth rate is 8–10% per annum. For energy, India depends on oil and gas imports, which accounts for over 65% of its consumption, it is likely to increase further considering the economic development, rise in the living standard of people and rising prices. Coal which currently accounts for over 60% of India's electricity production is the major source of emission of greenhouse gases and that of acid rains. In the business-as-usual scenario, India will exhaust its oil reserves in 22 years, its gas reserves in 30 years and its coal reserves in 80 years. More alarming, the coal reserves might disappear in less than 40 years if India continues to grow at 8% a year, Kalshian (2006).

An attempt to estimate the CO_2 mitigation potential of solar home system (SHS) in India by studying the potential for their diffusion and the appropriate baseline has been made by Chaurey and Kandpal (2009). They found that carbon finance could reduce the effective burden of SHS to the user by 19% if carbon prices are \$10/t CO_2 without transaction cost.

In this paper, energy and life cycle cost analysis (LCCA) of PVT array systems discussed namely: (a) opaque PVT array (b) solar cell tiles (SCT) array and (c) semi-transparent PVT array has been evaluated. The earlier studies for LCCA were carried out without incorporating the effect of EPBT due to which the actual life cycle cost was not reflected in the results. In the present study, an attempt has been made to introduce a new concept of investigation of life cycle cost of the PVT array systems by incorporating the effect of EPBT and carbon credits earned by the systems. The study will be helpful to closely relate the actual life cycle cost in conjunction with the performance of given system. The systems have been analyzed based upon overall thermal energy and exergy output for the climatic conditions of New Delhi, India.

2. System description

2.1. Opaque PVT array

The system consists of a PVT array (10.08 m × 2.16 m) having 36 numbers of PVT air collectors (opaque) [Fig. 1a(i)] and each PVT air collector (1.12 m × 0.54 m)

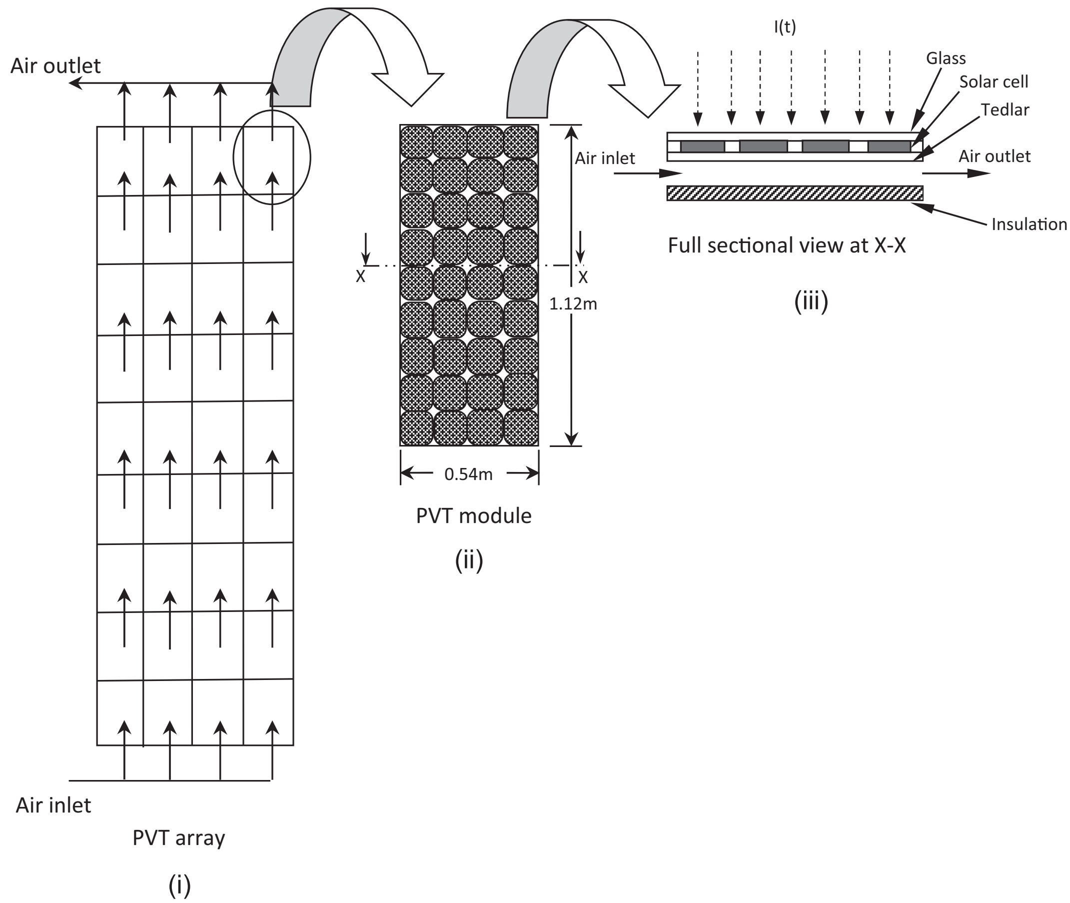

Fig. 1a. Case-A: Typical layout of a PVT array showing (i) flow configuration for (ii) enlarged view of a PV module and its (iii) full sectional view.

include 36 number of solar cells [Fig. 1a(ii)], the full sectional view of the PVT air collector is also shown [Fig. 1a(iii)]. It is considered as case A. If outlet of one PVT air collector is connected to the inlet of second PV module and outlet of second PV module is connected to inlet of third PV module and so on, then it is called series connection. If each row of PVT air collector has a common inlet and a common outlet then such configuration is called as parallel connection. A theoretical analysis and optimization is carried out on a proposed PVT array.

2.2. Solar cell tile array

The solar cell tile (SCT) array analyzed in the present study i.e. case-B has two integrated columns of 648 SCT in series which are connected in parallel. It is composed of 1296 numbers of identical SCT having dimensions 0.124 m × 0.124 m each. A typical layout of the SCT array has been shown in Fig. 1b(i) with the enlarged view of a SCT Fig. 1b(ii) and its full sectional view showing air flow in the duct Fig. 1b(iii). It should be noted that 1296 SCT's has been taken because 36 PVT modules considered correspond to 1296 silicon solar cells. Each SCT is a glass to tedlar (opaque) type tile and is arranged in the required configuration by joining each tile separately.

2.3. Semi transparent PVT array

For the present analysis of semi-transparent PVT array, the optimum configuration of the opaque PVT array (Fig. 1a) is taken into consideration while replacing the opaque PVT air collector with semi-transparent PVT air collector and referred as case-C. In this type of collector, the PV module is a glass to glass module where light can transmit through the non packing area.

3. Methodology

The life cycle energy analysis is carried out to quantify the energy in use and generation of energy through PVT air collectors. The analysis has been divided into two segments namely embodied energy and energy metrics. The computations of thermal and electrical energy have been obtained following the same the methodology described in previous chapters. The monthly thermal and electrical energy have been calculated by multiplying the total energy obtained in a day to number of clear day in a month. The overall thermal energy output is obtained by using following Eq. (1),

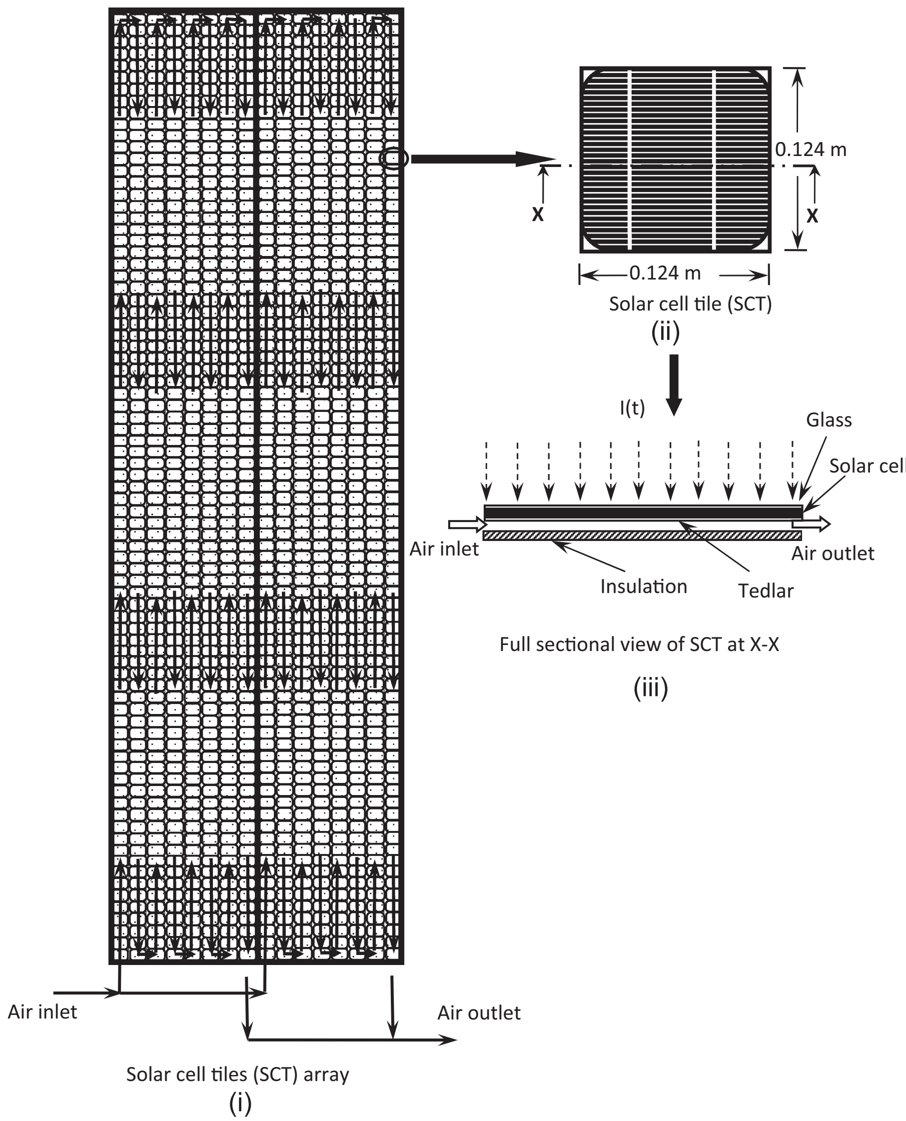

Fig. 1b. Case-B: Typical layout of solar cell tiles (SCT) array showing (i) flow configuration with an (ii) enlarged view of the SCT with its (iii) full sectional view.

$$\sum \dot{Q}_{u,overall} = \sum \dot{Q}_{u,thermal} + \frac{\sum \dot{E}x_{electrical}}{\eta_{cpower}} \tag{1}$$

where $\dot{Q}_{u,overall}$, $\dot{Q}_{u,thermal}$ and $\frac{\dot{E}x_{electrical}}{\eta_{cpower}}$ are overall thermal gain from a PVT system, thermal energy gain collected by the PVT system and equivalent thermal gain from electrical gain. The useful thermal energy gain from the array system is added to electrical gain. The electrical gain being high grade energy therefore, it is first converted into equivalent thermal energy output by dividing it with a factor called as 'electric power generation efficiency conversion factor of conventional power plant' this factor is usually taken as 0.38 for coal quality of India. The overall exergy output is obtained by using following Eq. (2).

$$\sum \dot{E}x_{thermal} + \sum \dot{E}x_{electrical} = \sum \dot{E}x_{overall} \tag{2}$$

$$\dot{E}x_{thermal} = \eta_{Carnot} \times \dot{Q}_{u,thermal} \tag{2a}$$

where the Carnot efficiency is given by, $\eta_{Carnot} = \left[1 - \frac{T_a+273}{T_{fo}+273}\right]$.

The rate of electrical energy gain (kWh) for N number of PVT air collectors (opaque and semi-transparent) connected in series and n_{pv} rows connected in parallel is given as,

$$\dot{E}x_{electrical} = n_{pv} \times \left[\frac{\sum_{i=1}^{N} \eta_{mi} \cdot I(t) \cdot A_m}{1000}\right] \tag{2b}$$

where η_{mi} is the temperature dependent electrical efficiency of module for ith PVT air collector connected in series.

The electrical energy gain (kW h), for n number of SCT air collector connected in series and n_{pv} rows connected in parallel is given as,

$$\dot{E}x_{electrical''} = n_{pv} \times \left[\frac{\sum_{i=1}^{n}\eta_{ci} \cdot A_c \cdot I(t)}{1000}\right] \tag{2c}$$

where η_{ci} is the temperature dependent electrical efficiency of solar cell for ith SCT air collector connected in series.

The useful thermal energy gain is converted to equivalent high grade energy by multiplying it with the Carnot efficiency and added to the electrical gain of the system. The daily average solar intensity of each month has been multiplied with the number of clear days in a month; the average monthly solar intensity is averaged to get the annual average solar intensity (E_{sol}).

3.1. Thermal modeling

The thermal model for useful thermal energy gain $\dot{Q}_{u,thermal}$ of opaque PVT array and SCT array has been considered from the studies carried out by Rajoria et al. (2012, 13) while the thermal modeling for semi-transparent PVT array is as follows:

(i) For cells of semi-transparent PVT air collector:

$$\alpha_c\tau_g\beta_c I(t)b \cdot dx = \left[U_{tc,a}(T_c - T_a) + U_{tc,f}(T_c - T_f)\right]b \cdot dx + \eta_m I(t)b \cdot dx \tag{3}$$

$$\begin{bmatrix}\text{The rate of solar energy}\\ \text{available on semi-}\\ \text{transparent PV module}\end{bmatrix} = \begin{bmatrix}\text{The rate of overall heat}\\ \text{loss from top surface of}\\ \text{cell to ambient}\end{bmatrix} + \begin{bmatrix}\text{The rate of overall}\\ \text{heat loss from cell}\\ \text{to flowing fluid}\end{bmatrix} + \begin{bmatrix}\text{The rate of electrical}\\ \text{energy produced}\end{bmatrix}$$

where $\eta_m = \eta_c\tau_g\beta_c$ and $U_{tc,f} = \left[\frac{L_g}{K_g} + \frac{1}{h_i}\right]$.

From Eq. (3), the expression for cell temperature is

$$T_c = \frac{\alpha_{eff} I(t) + U_{tc,a}T_a + U_{tc,f}T_f}{U_{tc,a} + U_{tc,f}} \tag{4}$$

where $\alpha_{eff} = (\alpha_c\tau_g\beta_c - \eta_m)$.

The temperature dependent electrical efficiency of silicon solar cell is given as, Agrawal and Tiwari (2011)

$$\eta_c = \eta_o[1 - \beta_o(T_c - T_{ref})] \tag{5}$$

(ii) For air flowing below the semi-transparent PVT air collector:

Assuming the absorptivity of blackened absorber surface to be 100%, the energy balance equation for air flowing below semi-transparent PVT air collector is given as

$$\dot{m}_f C_f\left(\frac{dT_f}{dx}\right)dx + U_b(T_f - T_a)b \cdot dx = \left[\tau_g^2(1 - \beta_c)I(t) + U_{tc,f}(T_c - T_f)\right]b \cdot dx \tag{6}$$

$$\begin{bmatrix}\text{Rate of heat transfer}\\ \text{to the flowing fluid}\end{bmatrix} + \begin{bmatrix}\text{Overall heat transfer from}\\ \text{flowing fluid to ambient}\end{bmatrix} = \begin{bmatrix}\text{Rate of heat transfer from packing and}\\ \text{non-packing areas to the flowing fluid}\end{bmatrix}$$

On substituting the expression of T_c from Eq. (4) into Eq. (6) and rearranging we get

$$\frac{dT_f}{dx} + \frac{bU_{L'}}{\dot{m}_f C_f}T_f = \left[\left(\tau_g^2(1-\beta_c) + h_{p'}\alpha_{eff}\right)I(t) + U_{L'}T_a\right]\frac{b}{\dot{m}_f C_f} \tag{7}$$

where $U_{L'} = (U_{ta'} + U_b)$, $U_{ta'} = \frac{U_{tc,f}U_{tc,a}}{U_{tc,a}+U_{tc,f}}$ and $h_{p'} = \frac{U_{tc,f}}{U_{tc,a}+U_{tc,f}}$.

Eq. (7) can be written into following form

$$\frac{dT_f}{dx} + aT_f = f(x) \tag{8}$$

The solution of the Eq. (8) can be written as

$$T_f = \frac{f(x)}{a}(1 - e^{-ax}) + T_{fi}e^{-ax}$$

Applying boundary conditions

At $x = 0$, $T_f = T_{fi}$ and at $x = L$, $T_f = T_{fo}$

$$T_{fo} = \left[\frac{\left(\tau_g^2(1-\beta_c) + h_{p'}\alpha_{eff}\right)I(t) + U_{L'}T_a}{U_{L'}}\right]\left(1 - e^{\frac{-bU_{L'}L}{\dot{m}_f C_f}}\right) + T_{fi}e^{\frac{-bU_{L'}L}{\dot{m}_f C_f}} \tag{9}$$

The average temperature of air flowing through the duct of semi-transparent PVT air collector is derived as

$$\bar{T}_{f'} = \frac{1}{L}\int_0^L T_f dx = \left[\frac{\left(\tau_g^2(1-\beta_c) + h_{p'}\alpha_{eff}\right)I(t)}{U_{L'}} + U_{L'}T_a\right]\left(1 - \frac{1 - e^{\frac{-bU_{L'}L}{\dot{m}_f C_f}}}{\frac{bU_{L'}L}{\dot{m}_f C_f}}\right) + T_{fi}\left(\frac{1 - e^{\frac{-bU_{L'}L}{\dot{m}_f C_f}}}{\frac{bU_{L'}L}{\dot{m}_f C_f}}\right) \tag{10}$$

The average air temperature of the first semi-transparent PVT air collector is substituted in Eq. (4) to get the average solar cell temperature of the first air collector which is again substituted in Eq. (5) to obtain the temperature dependent electrical efficiency of the first semi-transparent PVT air collector. The outlet air temperature of the first PVT air collector becomes the inlet air temperature of the second therefore, by following this condition; the average air temperature of the second PVT air collector is obtained to compute the temperature dependent efficiency of the second PVT air collector. This step is continued till the Nth semi-transparent PVT air collector connected in series is reached.

The outlet air temperature for Nth semi-transparent PVT air collectors connected in series can be derived as

$$T_{foN} = \left[\frac{(\tau_g^2(1-\beta_c)+h_{p'}\alpha_{eff})I(t)+U_{L'}T_a}{U_{L'}}\right]\left(1-e^{\frac{-NbU_{L'}L}{\dot{m}_f C_f}}\right) + T_{fi}e^{\frac{-NbU_{L'}L}{\dot{m}_f C_f}} \tag{11}$$

The rate of useful thermal energy gain for n_{pv} rows of semi-transparent PVT air collectors connected in parallel can be obtained as

$$\dot{Q}_{u,thermal} = n_{pv}\dot{m}_f C_f (T_{foN'} - T_{fi}) \tag{12}$$

Substituting the value of T_{foN} from Eq. (10) into Eq. (12) we get

$$\dot{Q}_{u,thermal} = n_{pv}\dot{m}_f C_f \left[\frac{\left(\tau_g^2(1-\beta_c)+h_{p'}\alpha_{eff}\right)I(t)}{U_{L'}} + T_a - T_{fi}\right] \times \left(1-e^{\frac{-NbU_{L'}L}{\dot{m}_f C_f}}\right) \tag{13}$$

3.2. Embodied energy

The concept of embodied energy is a relatively new area of environmental assessment that has started to be included in life cycle energy calculations of buildings. Embodied energy is defined as: *"the quantity of energy required by all of the activities associated with a production process, including the relative proportions consumed in all activities upstream to the acquisition of natural resources and the share of energy used in making equipments and in other supporting functions i.e. direct energy plus indirect energy"*, Treloar (1994). A hybrid method for analysis of embodied energy has been proposed by Crawford et al. (2006). The method allows comprehensive assessment of the combined energy used throughout the entire life-cycle of the PV systems the variation of EPBT was found between 4.0 and 16.5 years. It has also been investigated that the best option to reduce the EPBT of the PV system is to simultaneously generate thermal and electrical energy from the system.

Ito et al. (2010) have investigated the LCCA of the very large scale PV (VLS-PV) systems installed in desert area using sc-Si, mc-Si, a-Si/sc-Si, a-Si/lc-Si, CdTe and CIS PV modules. It has been found that the largest and smallest energy requirement came for sc-Si and CIS respectively and is average for mc-Si, a-Si/sc-Si, thin-film Si and CdTe. The EPBT of the CIS's VLS-PV system is approximately 1.8 years, 2.5 years for sc-Si. Also, the CO_2 emissions rate is observed as 43–54 g-CO_2/kW h. Further, a lower CO_2 emissions rate has been observed for mc-Si, a-Si/sc-Si and CIS.

Sharma and Tiwari (2013) evaluated the off-field and on-field overall performance of a stand-alone solar photovoltaic (SAPV) system. The EPBT and LCCA has been done incorporating embodied energy of the system. The analysis showed that the unit cost of electricity with actual on-field performance comes out to be Rs. 47.42/kW h as rooftop mounted system (without land cost) and Rs. 61.91/kW h as ground mounted system (with land cost).

Praseeda et al. (2015) have used process and input output analysis for assessment of embodied energy of building materials in India. Their results reflected a significant difference in Embodied energy of materials whose production involves significant electrical energy expenditure relative to thermal energy use. Their investigation revealed that, among the basic materials considered, aluminium coils have highest EE value followed by steel, glass and cement and in the masonry units burnt clay bricks have high EE (1.2–4.05 MJ/kg) followed by concrete blocks (0.17–0.25 MJ/kg) and laterite stone blocks (0.007 MJ/kg).

Thus the aim of any embodied energy analysis is to quantify the amount of energy used to manufacture a material or component. This involves the assessment of the overall expenditure of energy required to extract the raw material, manufacture a product or components, installation and maintain the component element whichever is being assessed. For the embodied energy analysis of the present PVT systems discussed, the total energy requirement for individual components with their manufacturing energy needs to be evaluated. The breakup of embodied energy of each component of fabrication of PVT air collectors have been tabulated in Table 2. The PV module is a high energy intensive component of the photovoltaic thermal air collectors. It is important to note that the energy density for manufacturing of opaque PV module, semi-transparent PV module and SCT is considered same.

3.3. Energy metrics

The performance of a PVT and SCT array system is computed using three basic metrics. These are the energy payback time (EPBT), the energy production factor (EPF) and the life cycle conversion efficiency (LCCE). The subsequent sections will show the methodology and formulae for the computation of these metrics.

3.3.1. Energy payback time (EPBT)

The EPBT depends on the energy spent to prepare the materials used for fabrication of the system and its components i.e. embodied energy and annual energy yield (output) obtained from such system. To evaluate the embodied energy of various components of a system, the energy densities of different materials are required. It is the total time required to recover the total energy required to recover the total energy spent to prepare the materials used for fabrication of a system.

It is the ratio of the total energy consumed in the production and installation of the system (E_{in}) to the total energy out (E_{out}).

$$\text{EPBT (years)} = \frac{E_{in}\ \text{(kW h)}}{E_{out}\ \text{(kW h/year)}} \tag{14}$$

3.3.2. Energy production factor (EPF)

The overall energy performance of the PVT system can be evaluated by comparing the total energy input to the total energy output. The ratio of these two quantities is referred as the energy production factor. It is used to predict the overall performance of the system (Agrawal, 2012; Rajoria et al., 2012). The energy production factor is a function of time because both E_{out} and E_{in} are time dependent and can be defined by two ways.

(i) On annual basis

$$\chi_a = \frac{E_{out}}{E_{in}} \quad \text{or,} \ \chi_a = \frac{1}{\text{EPBT}} \tag{15a}$$

If $\chi_a \to 1$, for EPBT = 1 the system is worthwhile otherwise it is not worth from energy point of view.

(ii) On life time basis

$$\chi_L = \frac{E_{out} \times T}{E_{in}} \tag{15b}$$

3.3.3. Life cycle conversion efficiency (LCCE)

This is the net energy productivity of the system with respect to the solar input (Radiation, E_{sol}) over the life time of the system (T, years) given by

$$\phi(t) = \frac{E_{out} \times T - E_{in}}{E_{sol} \times T} \tag{16}$$

4. Annualized uniform cost

Annualized uniform cost is defined as a product of the net present value of the system and capital recovery factor (CRF),

$$\text{Annualized uniform cost} = \text{Net present value(NPV)} \times \text{Capital recovery factor} \tag{17}$$

$$\text{CRF} = \frac{i(i+1)^n}{(i+1)^n - 1}$$

where n = number of years and i = interest rate per year.

Let P is present value and R is operational and maintenance cost per year and $R_{F,10}$, $R_{F,20}$,... is wood and fan replacement cost in every ten years. The line diagram for life cycle cost of PVT array system has been shown in Figs. 2a–2c, where Fig. 2a represents the conventional cash flow diagram for computation of life cycle cost of PVT array system while Fig. 2b shows the cash flow diagram by considering the effect of EPBT on the life cycle cost. In this method, the new NPV is computed from the point where EPBT is over. Fig. 2c shows the cash flow considering the effect of EPBT combined with carbon credits earned by the system. The net present value of the individual method can be evaluated as,

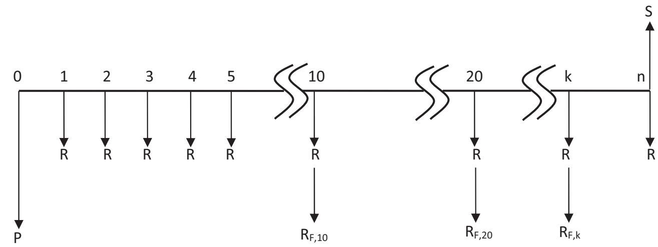

Fig. 2a. Conventional cash flow diagram for life cycle cost of PVT array system.

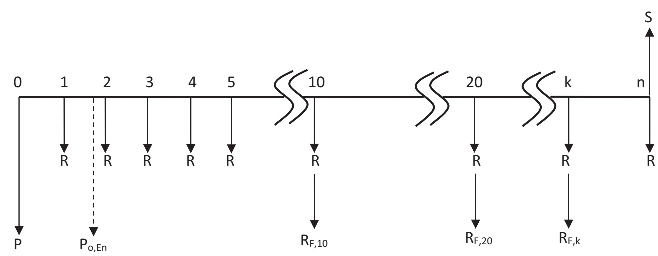

Fig. 2b. Cash flow diagram considering effect of EPBT for life cycle cost of PVT array system.

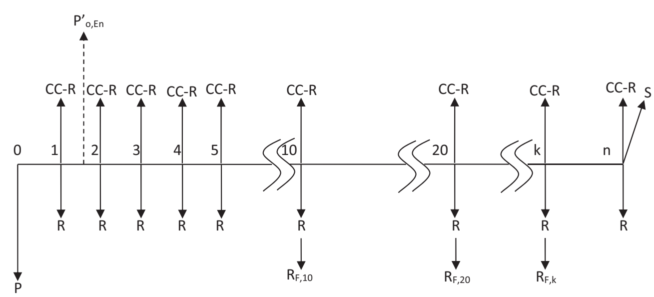

Fig. 2c. Cash flow diagram considering effect of EPBT combined with carbon credits earned for life cycle cost of PVT array system.

$$NPV = P + R_1 \times \left[\frac{(1+i)^n - 1}{i(1+i)^n}\right] + R_{F,10} \times \left[\frac{1}{(1+i)^{10}}\right] + R_{F,20} \times \left[\frac{1}{(1+i)^{20}}\right] + \ldots + R_{F,k} \times \left[\frac{1}{(1+i)^k}\right] + \ldots - S \times \left[\frac{1}{(1+i)^n}\right] \tag{18a}$$

$$NPV = P_{o,En} = P(1+i)^{En} + R \times (1+i)^{En-1} + R + R \times \left[\frac{(1+i)^{n-En} - 1}{i(1+i)^{n-En}}\right] + R_{F,10} \times \left[\frac{1}{(1+i)^{10-En}}\right] + R_{F,20} \times \left[\frac{1}{(1+i)^{20-En}}\right] + \ldots + R_{F,k} \times \left[\frac{1}{(1+i)^{k-En}}\right] + \ldots - S \times \left[\frac{1}{(1+i)^{n-En}}\right] \tag{18b}$$

where En = energy payback time (EPBT), R = annual operational and maintenance cost and R_F = fan replacement cost in every 10 years, S = salvage value.

$$\begin{aligned}\mathrm{NPV} = P'_{o,En} &= (CC-R)\times(1+i)^{En-1}+(CC-R)\\&+(CC-R)\times\left[\frac{(1+i)^{n-En}-1}{i(1+i)^{n-En}}\right]-R_{F,10}\times\left[\frac{1}{(1+i)^{10-En}}\right]-R_{F,20}\\&\times\left[\frac{1}{(1+i)^{20-En}}\right]-\ldots-R_{F,k}\times\left[\frac{1}{(1+i)^{k-En}}\right]\ldots+S\\&\times\left[\frac{1}{(1+i)^{n-En}}\right]-P(1+i)^{En}\end{aligned} \tag{18c}$$

5. Results and discussion

The value of various design parameters in the semi-transparent PVT array has been given in Table 1. In Fig. 3, the monthly variations of overall thermal energy gain by combining a–d type weather conditions of semi-transparent PVT array for Delhi has been shown. It has been observed that the overall thermal energy gain for case-C is higher than case-A for all the months while it is slightly lower in the month of June as compared to case-B. The month of June is the peak summer month and lowering of thermal gain for case-C in this month is due to higher dominance of air retention in tile concept of case-B subsiding the direct heat gain principle of case-C. The relative overall thermal energy gain for case-C in the month of May is higher by 20.4% and 0.04% against case-A & B respectively, while in June it is higher by 17.3% against case-A and lower by 0.38% against case-B. Also in July it is higher by 15.7% and 3.1% against case-A & B respectively. The monthly variation of overall exergy gain by combining a–d type weather conditions of PVT array for Delhi has been depicted in Fig. 4. It has been observed that overall exergy gain in the months of June and July for case-C comes lower than case-B because of the reason that these are the peak summer months responsible for boosting cell temperature to such an extent that even the larger heat extraction does not suffice to gain in electrical power of semi-transparent PVT array. The relative overall exergy gain for case-C in the month of May is higher by 15.9% and 0.35% against case-A & B respectively, while in June it is higher by 13.5% against case-A and lower by 0.67% against case-B. Similarly in July it is higher by 7.9% against case-A while lower by 0.49% against case-B.

Eqs. (14), (15a) and (15b), have been used for evaluating the energy payback time (EPBT) and energy production factor (EPF) of the system in terms of thermal energy and exergy. Energy payback time and energy production factor on an annual basis, considering annual energy and exergy of the system have been shown in Table 3. The minimum EPBT in terms of energy and exergy is 0.7 and 1.84 years respectively for case-C and maximum for case-A carrying a value of 0.84 and 2.17 years on energy and exergy basis respectively. The maximum value of EPF on annual basis in terms of energy and exergy is 1.42 and 0.54 respectively.

Table 1
Design parameters of semi-transparent PVT array.

Parameters	Values	Parameters	Values
A_m	0.605 m^2	$U_{td'}$	2.14 W/m^2 K
b	0.54 m	$U_{tc,a'}$	11.4 W/m^2 K
L	1.2 m	hp'	0.238
$\dot{m}_f$	0.001935 kg/s	N	36
C_f	1005 J/kg K	α_c	0.9
U_b	0.62 W/m^2 K	β_c	0.83
$U_{T'}$	66 W/m^2 K	η_o	0.12
$U_{L'}$	5.62 W/m^2 K	τ_g	0.95
$U_{tc,f}$	2.77 W/m^2 K		

The capital cost (P) and the salvage value (S) of PVT air collectors have been shown in Table 4.

Eqs. (16) and (17) have been used for evaluating the life cycle conversion efficiency (LCCE) and annualized uniform cost of the system in terms of thermal energy and exergy, while computation of NPV for the three different criterions has been done from Eqs. (18a)–(18c). The EPF and LCCE are evaluated by considering life time (n) of the system as 20, 25 and 30 years. Result shows that EPF and LCCE increase from case-A to case-C and the same increasing trend follows with increase in life time of the systems on both energy and exergy basis. The detailed results of EPF and LCCE on energy and exergy basis for all the cases have been shown in Table 5.

The maximum EPF has been observed for case-C for a life span of 30 years which is 42.68 and 16.28 on energy and exergy basis respectively, while minimum is for case-A for a life of 20 years which is 23.86 and 9.23 on energy and exergy basis respectively. Similarly the highest LCCE observed energetically and exergetically is 0.71 and 0.39 respectively for case-C with a life span of 30 years.

Tables 6a and 6b shows the effect on annualized uniform cost by varying the interest rate with 8%, 10% and 12% without and with considering the effect of EPBT respectively. It has been observed that the annualized uniform cost (Rs./kW h) is highest for case-B and lowest for case-C at a given life span and interest rate on both energy and exergy basis. Also, considering the effect of EPBT, the annualized uniform cost has increased by 3.1% for lowest value and 6.7% for the highest value on both energy and exergy basis.

The variation of annualized uniform cost on energy basis against expected life of the systems at different rates of interest has been plotted and shown in Figs. 5a and 5b. Fig. 5a shows the annualized uniform cost without considering the effect of EPBT of the systems while Fig. 5b shows the annualized uniform cost considering the effect of EPBT. It has been observed in both the figures that case-B has the highest annualized cost while case-C has the lowest and case-A lies in the middle. Here the annualized cost (Rs./kW h) is an indicative of cost of energy incurred in the system (negative sign) and hence, it can be inferred that a system which is having a lower value is a better system.

5.1. Carbon credits earned by PVT array systems

Total carbon credits earned by PVT array systems on the life time basis has been calculated on the basis of

Table 2
Break up of embodied energy of different components of opaque PVT array system (Barnwal and Tiwari, 2008; Tiwari et al., 2009).

S. no.	Component	Quantity (kg)	Energy density (kW h/kg)	Total embodied energy[a] (kW h)
1	M.S. support structure			
	(i) Steel angle	400	8.89	3556
	(ii) Screw	10	8.89	88.9
	(iii) Nut and bolt	25	8.89	222.25
2	PVC sheet	100	25.64	2564
3	Paint, kg	15	25.11	376.65
4	D C fan			
	(i) Aluminium	100	55.28	5528
	(ii) Iron	50	8.89	444.5
	(iii) Plastic	20	19.44	388.8
	(iv) Copper wire	50	19.61	980.5
		m^2	kW h/m^2	
5	PV module (glass-tedlar type, i.e. case-A), m^2	21.7	980	21,266
	Total			35415.6

[a] The total embodied energy for SCT array (i.e. case-B) and semi-transparent PVT array (case-C) will be the same due to same energy density involved in manufacturing of both systems including all the components.

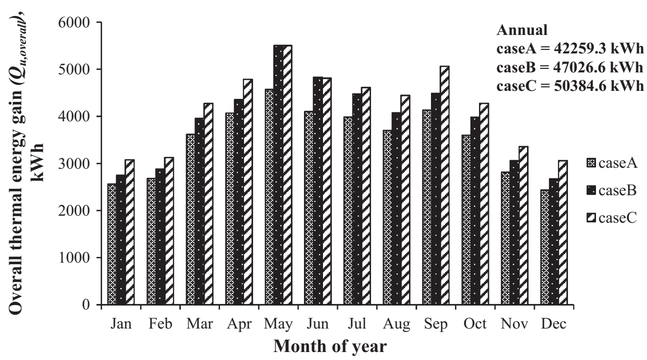

Fig. 3. Monthly variations of overall thermal energy gain by combining a–d type weather conditions of PVT array for Delhi.

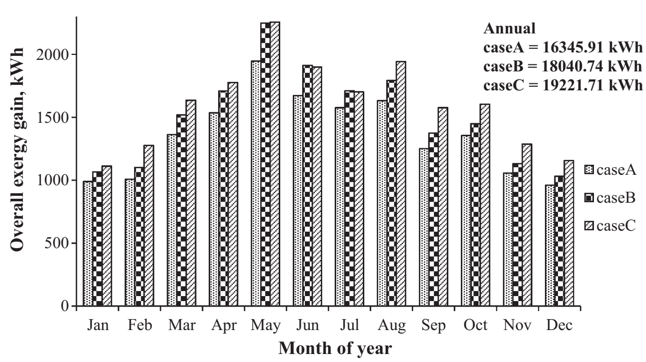

Fig. 4. Monthly variations of overall exergy gain by combining a–d type weather conditions of PVT array for Delhi.

overall thermal energy and exergy gain by the system. The calculations for carbon credits earned for case-A, over the life of 20 years has been shown below. Similar calculations have been carried out for other cases and the results have been tabulated in Table 7.

5.1.1. Overall thermal energy basis

Total overall thermal energy produced per annum = 42259.3 kW h.

If unit power is used by a consumer and the losses due to poor domestic appliances are around 20%, then the transmitted power should be $\frac{1}{1-0.2} = 1.25$ units. If the transmission and distribution losses are 40%, which is common in Indian conditions, then the power that has to be generated in the power plant is $\frac{1.25}{1-0.4} = 2.08$ units. The average carbon dioxide (CO_2) equivalent intensity of electricity generation from coal is approximately 0.982 kg of CO_2/kW h at source (Watt et al., 1998; Nawaz and Tiwari, 2006). Thus, for unit power consumption by the consumer the amount of CO_2 emission is $2.08 \times 0.982 = 2.04$ kg.

So, the carbon dioxide emission reduction per annum

$$= 42259.3 \times 2.04 = 86.2\ tCO_2e \quad (1\ \text{ton} = 10^3\ \text{kg})$$

If carbon dioxide emission reduction at present is being traded @ €21/tCO_2e (Agrawal and Tiwari, 2013), then the carbon emission reduction by air collectors is equal to $= 86.2 \times 21 \times 71.72 =$ Rs. 1.29 lakhs per annum (where € 1 = Rs. 71.72; January, 2013).

Table 3
Energy payback time and energy production factor on annual basis, considering annual energy and exergy of the PVT air collectors.

Basis	Energy payback time (EPBT)			Energy production factor (EPF)		
	case-A	case-B	case-C	case-A	case-B	case-C
Energy	0.84	0.75	0.70	1.19	1.33	1.42
Exergy	2.17	1.96	1.84	0.46	0.51	0.54

Table 4
Capital cost (P_s), salvage value (S) and maintenance cost (M_s) of PVT array systems.

Components	Qty	PVT air collector	Salvage value of different components (S) at the inflation rate of 4% present values of scrap for, Iron @Rs. 15/kg		
		Rs.	After 20 year Iron scrap @Rs. 33/kg	After 25 year Iron scrap @Rs. 40/kg	After 30 year Iron scrap @Rs. 49/kg
Mild steel support structure @ Rs. 50/kg	400 kg	20,000	13,200	16,000	19,600
PV module/tile for					
(i) case-A @ Rs. 12,000/75W$_P$	36 nos.	4,32,000	18,000	18,000	18,000
(ii) case-B @ Rs. 500/PVT tile	1296 nos.	6,48,000	22,000	22,000	22,000
(iii) case-C @ Rs. 15,500/75W$_P$	36 nos.	5,58,000	18,000	18,000	18,000
DC fan	1 nos.	4800	252	252	252
Paint @ Rs. 80/kg	15 kg	1200	–[a]	–[a]	–[a]
Fabrication charges		10,000	–[a]	–[a]	–[a]
Capital cost (Rs.)					
(i) case-A		4,68,000	31,452	34,252	37,852
(ii) case-B		6,84,000	35,452	38,252	41,852
(iii) case-C		5,84,000	31,452	34,252	37,582

Operational and maintenance cost = Rs. 500/- per year.
DC fan replacement cost and paint = Rs. 600/- in every ten years.
[a] No salvage value.

Table 5
EPF and LCCE on annual overall thermal energy and exergy basis for PVT array systems.

Life (years)	Cases	EPF		LCCE	
		Energy	Exergy	Energy	Exergy
20	case-A	23.86	9.23	0.58	0.21
	case-B	26.56	10.19	0.65	0.23
	case-C	28.45	10.85	0.70	0.25
25	case-A	29.83	11.54	0.59	0.22
	case-B	33.20	12.73	0.66	0.24
	case-C	35.57	13.57	0.71	0.26
30	case-A	35.80	13.85	0.59	0.33
	case-B	39.84	15.28	0.66	0.36
	case-C	42.68	16.28	0.71	0.39

Table 6a
Variation of annualized uniform cost for various interest rates and life time of system on energy and exergy basis without considering the effect of EPBT.

Life (years)	Cases	Annualized uniform cost (Rs./kW h)					
		$i = 0.08$		$i = 0.1$		$i = 0.12$	
		Energy	Exergy	Energy	Exergy	Energy	Exergy
20	case-A	−1.12	−2.91	−1.30	−3.36	−1.49	−3.84
	case-B	−1.48	−3.85	−1.71	−4.45	−1.95	−5.08
	case-C	−0.98	−2.56	−1.13	−2.96	−1.29	−3.38
25	case-A	−1.04	−2.69	−1.22	−3.17	−1.42	−3.67
	case-B	−1.36	−3.55	−1.61	−4.19	−1.86	−4.85
	case-C	−0.90	−2.36	−1.06	−2.78	−1.23	−3.23
30	case-A	−0.99	−2.56	−1.18	−3.06	−1.38	−3.58
	case-B	−1.30	−3.38	−1.55	−4.04	−1.81	−4.73
	case-C	−0.86	−2.25	−1.03	−2.69	−1.20	−3.15

Table 6b
Variation of annualized uniform cost for various interest rates and life time of system on energy and exergy basis considering the effect of EPBT.

Life (years)	Cases	Annualized uniform cost (Rs./kW h)					
		$i = 0.08$		$i = 0.1$		$i = 0.12$	
		Energy	Exergy	Energy	Exergy	Energy	Exergy
20	case-A	−1.19	−3.07	−1.36	−3.51	−1.59	−4.10
	case-B	−1.56	−4.06	−1.78	−4.65	−2.08	−5.42
	case-C	−1.01	−2.66	−1.16	−3.04	−1.35	−3.54
25	case-A	−1.08	−2.79	−1.27	−3.27	−1.49	−3.86
	case-B	−1.42	−3.69	−1.66	−4.34	−1.96	−5.11
	case-C	−0.92	−2.42	−1.08	−2.84	−1.27	−3.34
30	case-A	−1.01	−2.62	−1.22	−3.16	−1.45	−3.74
	case-B	−1.33	−3.48	−1.61	−4.19	−1.90	−4.95
	case-C	−0.87	−2.28	−1.05	−2.74	−1.23	−3.24

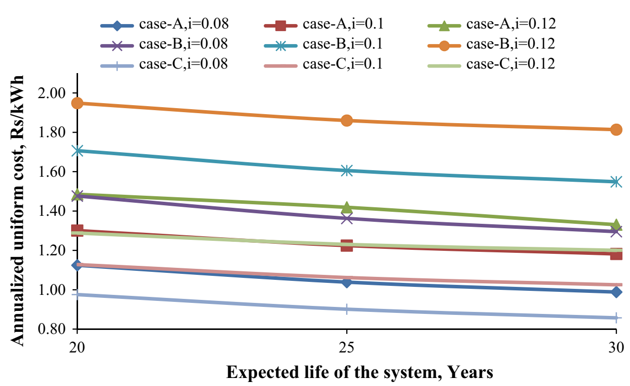

Fig. 5a. Variation of annualized uniform cost without considering effect of EPBT at different life span of PVT array systems.

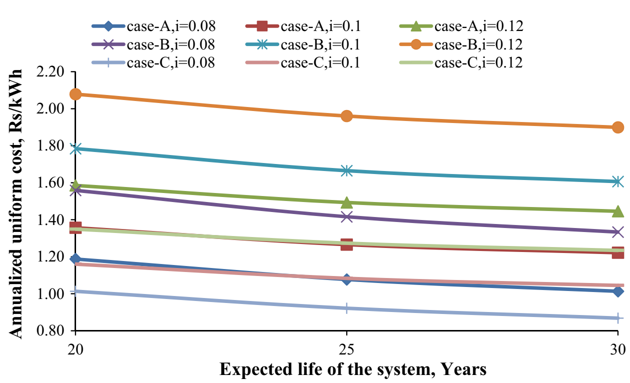

Fig. 5b. Variation of annualized uniform cost considering the effect of EPBT at different life span of PVT array systems.

For the lifetime (20 year) analysis, the carbon emission reduction by air is equal to $= 25.9 \times 20 =$ Rs. 25.96 lakhs.

5.1.2. Overall exergy basis

Total overall exergy generated per annum = 16345.9 kW h.

The carbon dioxide emission reduction per annum

$$= 16345.9 \times 2.04 = 33.3\ tCO_2e.$$

If carbon dioxide emission reduction at present being traded @ €21/tCO_2e (European Climate Exchange, 2008), then the carbon emission reduction by air heaters is equal to $= 33.3 \times 21 \times 71.72 =$ Rs. 50222.5 per annum (where € 1 = Rs. 71.72; January, 2013).

For the life time (20 year) analysis, the carbon emission reduction by air collectors is equal to $= 50222.5 \times 20 =$ Rs. 10.04 lakhs.

The combined effect of carbon credits earned and EPBT on annualized uniform cost at various interest rates and life span of the PVT array systems has been shown in Table 8. It has been observed that going from lower to higher rates of interest, the annualized uniform cost decreases for all the cases and an increasing trend is followed at higher life span of the systems. Also, among all the cases, the lowest values comes for case-B and highest for case-C on both energy and exergy basis. While considering the effect of carbon credits earned by the systems. The higher value of annualized uniform cost is indicative of better and efficient system which has the capability to compensate the cost incurred in the system. The semi-transparent PVT array produces the

Table 7
CO_2 mitigation and carbon credits earned by PVT array systems.

Cases	Carbon dioxide mitigation (tCO_2e/annum)		Total carbon credits earned for lifetime (Rs.)					
			20 years		25 years		30 years	
	Energy	Exergy	Energy	Exergy	Energy	Exergy	Energy	Exergy
case-A	86.2	33.3	2,596,821	1,004,451	3,246,026	1,255,563	3,895,232	1,506,676
case-B	95.9	36.8	2,889,770	1,108,596	3,612,213	1,385,744	4,334,655	1,662,893
case-C	102.8	39.2	3,096,118	1,181,168	3,870,148	1,476,460	4,644,178	1,771,751

Table 8
Variation of annualized uniform cost for various interest rates and life time of system on energy and exergy basis considering the effect of carbon credits earned and EPBT.

Life (years)	Cases	Annualized uniform cost (Rs./kW h)					
		$i = 0.08$		$i = 0.1$		$i = 0.12$	
		Energy	Exergy	Energy	Exergy	Energy	Exergy
20	case-A	2.39	6.19	2.23	5.76	2.13	5.50
	case-B	2.01	5.23	1.79	4.68	1.62	4.22
	case-C	2.56	6.70	2.43	6.36	2.36	6.18
25	case-A	2.42	6.26	2.27	5.87	2.15	5.57
	case-B	2.07	5.40	1.87	4.86	1.68	4.37
	case-C	2.57	6.75	2.46	6.44	2.37	6.22
30	case-A	2.44	6.30	2.31	5.96	2.17	5.60
	case-B	2.11	5.50	1.92	4.99	1.71	4.45
	case-C	2.58	6.77	2.49	6.52	2.38	6.25

highest annual overall thermal energy and exergy as compared to opaque PVT array and SCT array and therefore, will earn highest carbon credits as shown in Table 7. Therefore, it can be inferred that the results case-C is an efficient performer followed case-A and case-B.

6. Conclusions

On the basis of the present study, the conclusions of the paper are as follows:

- The annual overall thermal energy gains for case-A, B and C are 42259.3 kW h, 47026.6 kW h and 50384.6 kW h respectively and exergy gains are 16345.91 kW h, 18040.74 kW h and 19221.71 kW h respectively. The variation of gain depends upon the number of clear days falling in each month.
- The minimum EPBT in terms of energy and exergy is 0.70 and 1.84 years respectively for case-C and maximum for case-A carrying a value of 0.84 and 2.17 years on energy and exergy basis respectively.
- The lowest and highest EPF and LCCE values on energy and exergy basis fall for case-A and case-C respectively while case-B falls in the middle. The maximum EPF has been observed for case-C for a life span of 30 years which is 42.68 and 16.28 on energy and exergy basis respectively and the highest value of LCCE energetically and exergetically is 0.71 and 0.39 respectively.
- When effect of EPBT is considered in the cash flow of the PVT array system, the annualized uniform cost has increased by 3.1% for lowest value and 6.7% for highest value on both energy and exergy basis. The values reflected this approach is more realistic than the conventional approach.
- The annualized cost (Rs./kW h) with and without consideration of effect of EPBT is an indicative of cost of energy incurred (negative sign) in the system and hence, the system having a lower value is a better system.
- While considering the effect of carbon credits earned and EPBT on annualized uniform cost of the PVT array system, the higher value of annualized uniform cost is indicative of better and efficient system which has the capability to compensate the cost incurred in the system.
- Among all the cases, case-C is a better performer in terms of energy and exergy.

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