CHAPTER-V

ANALYSIS OF VARIOUS HYBRID PVT SYSTEMS
5.1 Introduction

Photovoltaic thermal (PVT) technology can be used for numerous purposes in day to day life. It is not only used in households but also for industrial applications. It can also play a significant role in reducing conventional energy requirements in today’s global scenario of energy crisis. PVT can also play an important role in the mitigation of greenhouse gases. Depending on the fluid (air or water) used for removing the thermal energy associated with the bottom of the PV module, PVT system is also referred as hybrid PVT air collector or hybrid PVT water collector. Hybrid PVT air collectors consist of a PV module with an air duct mounted below the module. Air gets heated by using the thermal energy available at the back of the PV module (tedlar). In case of a hybrid PVT water collector, a water heat exchanger is integrated below the PV module. Water gets heated by using the thermal energy available at the bottom of the PV module.

In applications of hybrid PVT system, the production of electricity is the main priority since it is high grade energy and therefore, it is necessary to operate the PV modules at low temperature in order to keep the PV cell electrical efficiency at a sufficient level. Natural or forced air circulation is simple and low cost methods to remove heat from PV module but they are less effective, if the ambient air temperature is over 25°C. To overcome this effect, the heat can be extracted by circulating water/air under forced mode through a heat exchanger that is mounted at the rear surface of the PV module. Hybrid PVT System provides higher energy.

5.2 Thermal modeling

Energy balance equations can be written with the help of following assumptions -

1) The framework is in semi relentless state condition.
2) Ohmic misfortunes in solar cell are immaterial.
3) The warmth exchange coefficient is steady.
4) The wind current through conduit is uniform for the constrained method of operation for stream.

5) Heat capacity of the solar cell is neglected.

6) Temperature inclination is missing along the thickness of solar cell.

![Diagram](image)

**Figure 5.1** A elemental length $dx$ indicating stream example of air

The energy balance equations can be written by following Tiwari et al. [30] and Joshi [65]-

### 5.2.1 Module I: Opaque PV module having air duct below PV module

In this type of opaque PV module, duct was made below the module. Here when solar radiation falls on PV module, there will be a generation of electricity. Heat loss from the PV back of PV module gets absorbed by tedlar which will be then further used in heating of air flowing in the duct. Schematic diagram of given module is shown in the Figure 4.1. The cross-section view and energy flow diagram of is shown in the Figure 5.2 (a) and (b).

i) For solar cell of PV module:

$$P_{1T} + P_{2T} = P_{3T} + P_{4T} + P_{5T}$$  \hspace{1cm} (5.1a)

$$P_{1T} = \tau_e \alpha_c I(t) \beta_c b_d x$$ = rate of solar energy received by solar cell after transmission
\[ P_{2T} = \tau_g (1-\beta_c) \alpha_T I(t) b d x = \text{rate of solar energy absorbed by tedlar after transmission from non packing area of module.} \]

Figure 5.2 (a): Cross-section view of opaque PV module having air duct below the module

Figure 5.2 (b): Energy flow diagram
\[ P_{3T} = U_t(T_c - T_a)bd_x = \text{rate of heat loss from solar cell to ambient through glass cover} \]

\[ P_{4T} = U_T(T_c - T_{bs})bd_x = \text{rate of heat transfer from solar cell to back surface} \]

\[ P_{5T} = \alpha_c \eta_c \beta_c I(t) \tau_g bd_x = \text{rate of electrical energy produced} \]

\[ P_{4T} = P_{6T} \]  \hspace{1cm} (5.1 b)

\[ P_{6T} = h_T(T_{bs} - T_{air})bd_x = \text{rate of heat loss from back surface to flowing air} \]

\[ P_{7T} = P_{4T} + P_{8T} \]  \hspace{1cm} (5.1 c)

\[ P_{8T} = U_{bi}(T_{air} - T_a)bd_x = \text{rate of heat loss from flowing air to ambient through insulation} \]

With the help of above Eqs. an expression for solar cell temperature can be obtained as:

\[ T_c = \frac{\tau_g \beta_c \alpha_c + \alpha_T(1 - \beta_c) - \eta_c \beta_c I(t) + U_t T_a + U_T T_{bs}}{U_t + U_T} \]  \hspace{1cm} (5.1 d)

With the help of Eqs. (5.1 b) and (5.1 d), back surface temperature can be written as:

\[ T_{bs} = \frac{h_p I(\alpha_T)_{eff} T(t) + U_{tT} T_a + h_T T_{air}}{h_T + U_{tT}} \]  \hspace{1cm} (5.1 e)

Putting values of \( T_c \) & \( T_{bs} \) in Eqn. (5.1 c) and rearranging them, we get

\[ \frac{dT_{air}}{dx} + \left( \frac{bU_LT}{m_a \rho_c} \right) (T_{air} - T_a) = \frac{bh_p I h_{p2T} (\alpha_T)_{eff} T(t)}{m_a \rho_c} \]  \hspace{1cm} (5.1 f)
Integrating Eqn. (5.1 f) and applying the initial condition i.e at \( x=0 \), \( T_{air} = T_{airin} \), temperature of air flowing inside air duct is obtained:

\[
T_{air} = T_{airin} + \left[ T_{a} + \frac{h_{p1}T_{h}p_{2T}(\alpha_{e})effT_{(t)}}{U_{LT}} \right] \times \left[ \frac{-bU_{LT}x}{m_{a}c_{a}} \right] \times \left[ 1 - e^{-\frac{-bU_{LT}x}{m_{a}c_{a}}} \right] + T_{airin} e^{-\frac{-bU_{LT}x}{m_{a}c_{a}}} \tag{5.1g}
\]

The normal air temperature of the air streaming inside the air conduit can be utilized to get the back surface temperature of a PV module from comparison (5.1 e). At long last, solar cell temperature for given atmosphere parameters can be effortlessly gotten. The rate of usefull heat energy can be gotten by putting the quantities in Eqn. (1.7 f) and accordingly can be acquired as:

\[
Q_{thermal} = \frac{m_{a}c_{a}}{U_{LT}} \left[ h_{p1}T_{h}p_{2T}(\alpha_{e})effT_{(t)}} - U_{LT} \left( T_{airin} - T_{a} \right) \right] \left[ 1 - e^{-\frac{-bU_{LT}x}{m_{a}c_{a}}} \right] \tag{5.1i}
\]

The temperature dependent electrical efficiency can be calculated by using Eqn. (1.6) and can thus be obtained as:
\[ \eta_{cl} = \eta_0 \left[ 1 - \beta_0 \left[ \frac{a_c \beta_c + a_T (1 - \beta_c)}{U_T + U_t} \right] \left[ 1 + \frac{U_{1T}^h p_{1T}}{h_T + U_{1T}} + \frac{U_{2T}^h p_{1T}^h p_{2T}}{h_T + U_{2T}} \left( 1 - \frac{1 - \exp(-x_0)}{x_0} \right) \right] \right] \\
\]

(5.1 j)

here \( x_0 = \frac{b U_{LT} L}{m'a_c} \)

### 5.2.2 Module II: Opaque PV module having air duct above the module

In this type of opaque PV module as shown in the Figure 4.3, a duct of glass is made above the PV module. Here flowing air in the duct absorbs heat by solar radiation and also from various conductive and convective losses. The cross-section view and energy flow diagram is shown in the Figure 5.3 (a) & (b).

Figure 5.3 (a): Cross-section view of opaque PV module having air duct above the module

i) For solar cell of PV module:

\[ P_{1TG} + P_{2TG} = P_{3TG} + P_{4TG} + P_{5TG} \]  

(5.2 a)
\[ P_{1TG} = \tau_g^2 \alpha_c^2 I(t) \beta_c bd_x \] = rate of solar energy received by solar cell after transmission

\[ P_{2TG} = \tau_g^2 (1 - \beta_c) \alpha_c^2 I(t) bd_x \] = rate of solar energy absorbed by tedlar after transmission from non packing area of module.

\[ P_{3TG} = U_{ts} (T_c - T_{air}) bd_x \] = rate of heat loss from solar cell to air

\[ P_{4TG} = U_{bs} (T_c - T_a) bd_x \] = rate of heat loss from solar cell to ambient

\[ P_{5TG} = \eta_c \beta_c I(t) \alpha_c^2 \tau_g^2 bd_x \] = rate of electrical energy produced

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Figure 5.3(b): Energy flow diagram

ii) For air flowing through the duct:

\[ P_{3TG} = P_{6TG} + P_{7TG} \]  \hspace{1cm} (5.2 b)
\[ P_{6TG} = m_a c_a \frac{dT_{air}}{dx} \text{ = heat carried away with flowing air} \]

\[ P_{7TG} = h_1 (T_{air} - T_a) bd_x \text{ = rate of heat loss from flowing air to ambient} \]

Thus solar cell temperature expression can be obtained as:

\[ T_c = \frac{\left( \tau_g^2 \beta_c q_c^2 + \tau_g a_T (1 - \beta_c) - \tau_g^2 \eta_c \beta_c g_c^2 \right) I(t) + U_{bs} T_a + U_{ts} T_{air}}{U_{ts} + U_{bs}} \]  \hspace{1cm} (5.2 c)

Rearranging Eqn. (5.2 a) & (5.2 b) and (5.2 c)

\[ \frac{dT_{air}}{dx} + \left( \frac{bU_{LTG}}{m_a c_a} \right) (T_{air} - T_a) = \frac{bh p_{ITG} (\alpha \tau)_{effTG} I(t)}{m_a c_a} \]  \hspace{1cm} (5.2 d)

An expression for temperature of air flowing inside air duct can be obtained by integrating Eqn. (5.2 d) and applying initial condition i.e at \( x=0 \),

\[ T_{air} = T_{air in} \]

\[ T_{air} = T_a + \left( \frac{h p_{ITG} (\alpha \tau)_{effTG} I(t)}{U_{LTG}} \right) \times \left( \frac{-bU_{LTG} x}{m_a c_a} \right) + T_{air in} e^{\frac{-bU_{LTG} x}{m_a c_a}} \]  \hspace{1cm} (5.2 e)

Outlet air temperature can be obtained as:-

\[ T_{air out} = \frac{1}{L} \int_0^L T_{air} \, dx \]
At long last, solar cell temperature for given atmosphere parameters can be effortlessly gotten. The rate of productive warm energy can be gotten by putting the quantities in Eqn. (1.7 f) and accordingly can be acquired as:

\[
Q_{\text{thermal}} = \frac{m_a c_a}{U_{\text{LTG}}} \left[ h_{\text{LTG}} (\alpha t)_{\text{eff}} T(t) - U_{\text{LTG}} (T_{\text{airin}} - T_a) \right] \left( 1 - e^{-\frac{m_a c_a}{b U_{\text{LTG}}}} \right) \left( 1 - e^{-\frac{b U_{\text{LTG}} L}{m_a c_a}} \right)
\]  

(5.2 g)

The temperature dependent electrical efficiency can thus be obtained from Eqn. (1.6)

\[
\eta_{\text{el}} = \eta_0 \left[ 1 - \frac{\beta_0 (\alpha t)_{\text{eff}} T(t)}{U_{\text{ts}} + U_{bs}} \left\{ 1 + \frac{U_{\text{ts}} h_{\text{LTG}}}{U_{\text{LTG}}} \left( 1 - \frac{1 - \exp(-x_0)}{x_0} \right) \right\} \right]
\]

\[
\times \left[ 1 - \frac{\eta_0^2 \tau_g}{U_{\text{ts}} + U_{bs}} \left\{ 1 + \frac{U_{\text{ts}} h_{\text{LTG}}}{U_{\text{LTG}}} \left( 1 - \frac{1 - \exp(-x_0)}{x_0} \right) \right\} \right]
\]

(5.2 h)

here \(x_0 = \frac{b U_{\text{LTG}} L}{m_a c_a}\)

5.2.3 Module III: Semitransparent PV module having air duct below PV module:

The schematic diagram of semitransparent PV module having duct below PV module is shown in the Figure 4.2. Here when solar radiation falls on solar cell gets converted into electricity and also gets absorbed by black
The air flowing in the duct get heated by conductive as well as convective losses.

i) For solar cell of PV module:

\[ P_{1G} = P_{2G} + P_{3G} + P_{4G} \]  \hspace{1cm} (5.3 a)

\[ P_{1G} = \tau_g \alpha_c I(t) \beta_c \text{bd}_x \] = rate of solar energy received by solar cell after transmission

\[ P_{2G} = U_{TC} (T_c - T_a) \text{bd}_x \] = rate of heat loss from solar cell to ambient through glass cover

\[ P_{3G} = U_{TC} (T_c - T_{air}) \text{bd}_x \] = rate of heat loss from solar cell to air.

\[ P_{4G} = \eta_c \alpha_c \beta_c I(t) \tau_g \text{bd}_x \] = rate of electrical energy produced

Figure 5.4 (a): Cross-section view of semitransparent PV module having air duct below PV module
ii) Energy balance for back surface

\[ P_{5G} = P_{6G} + P_{7G} \]  

\[ P_{5G} = a_b \tau_g (1 - \beta_c) I(t)b_d x = \text{rate of solar energy absorbed by back surface after transmission from non packing area of module.} \]

\[ P_{6G} = h_{bf} (T_{bs} - T_{air}) b_d x = \text{rate of heat loss from back surface to flowing air} \]

\[ P_{7G} = U_{bp} (T_{bs} - T_a) b_d = \text{rate of heat loss from back surface to ambient temp.} \]

iii) For air flowing through the duct

\[ P_{8G} = P_{3G} + P_{6G} \]

\[ P_{8G} = m_a c_a \frac{dT_{air}}{dx} dx = \text{heat carried away with flowing air} \]

With the help of above Eqs., solar cell temperature expression can be obtained as:
\[ T_c = \frac{\left( \tau_g \beta_c \eta_c (1 - \eta_c) \right) I(t) + U_{tc} T_a + U_{Tc} T_{air}}{U_{tc} + U_{Tc}} \]  

(5.3d)

With the help of Eqs. (5.3a) and (5.3d), back surface temperature can be written as:

\[ T_{bs} = \frac{\alpha_b \left( 1 - \beta_c \right) \tau_g 2 I(t) + U_{bp} T_a + h_{pf} T_{air}}{h_{pf} + U_{bp}} \]  

(5.3e)

Putting the values from Eqs. (5.3d) and (5.3e) in Eqn. (5.3c) and rearranging them, we get

\[ \frac{dT_{air}}{dx} + \left( \frac{bU_{LG}}{m_a c_a} \right) (T_{air} - T_a) = \frac{b(\alpha t)_{eff} G I(t)}{m_a c_a} \]  

(5.3f)

Integrating Eqn. (5.3f) and applying initial conditions \( T_{air} = T_{air\infty} \) at \( x=0 \), an expression for temperature of air flowing inside air duct is obtained as:

\[ T_{air} = T_a + \frac{b(\alpha t)_{eff} G I(t)}{U_{LG}} \times \left( \frac{-bU_{LG}^x}{m_a c_a} \right) + T_{air\infty} e^{\frac{-bU_{LG}^x}{m_a c_a}} \]  

(5.3g)

Outlet air temperature over the complete length of duct is given by:

\[ T_{airout} = \frac{1}{L} \int_0^L T_{air} \, dx \]

\[ T_{airout} = T_a + \frac{(\alpha t)_{eff} G I(t)}{U_{LG}} \times \left( 1 - \frac{-bU_{LG}^L}{m_a c_a} \right) + T_{air\infty} \left( 1 - \frac{-bU_{LG}^L}{m_a c_a} \right) \]  

(5.3h)

The normal air temperature of the air streaming inside the air conduit can be utilized to get the back surface temperature of a PV module from comparison Eqn. (5.3 e). At long last solar cell temperature for given atmosphere parameters can be effortlessly gotten. The rate of useful heat gain can be gotten by putting the values in Eqn. (1.7 f) and accordingly can be acquired as:
\[ Q_{\text{thermal}} = \frac{m_a c_a}{U_{LG}} \left[ (\alpha \tau)_{\text{eff}} I(t) - U_{LG} \left( T_{\text{air}} - T_a \right) \right] \left( 1 - e^{-\frac{bU_{LG} L}{m_a c_a}} \right) \quad (5.3 \text{i}) \]

From Eqn. (1.6) temperature dependent electrical efficiency can thus be written as:

\[ \eta_{el} = \eta_0 \left[ 1 - \frac{\tau_g \beta_0 I(t)}{U_{TC} + U_{Tc}} \left( a_c \beta_c + \frac{U_{Tc} h_{LG}}{U_{LG}} \left( h_{p1G} a_c \beta_c + h_{p2G} a_b (1 - \beta_c) \tau_g \right) \frac{1 - \exp(-x_0)}{x_0} \right) \right] \]

\[ 1 - \frac{\eta_0 \beta_0 \tau_g a_c \beta_c I(t)}{U_{TC} + U_{Tc}} \left( 1 - \frac{U_{Tc} h_{LG}}{U_{LG}} \left( 1 - \frac{1 - \exp(-x_0)}{x_0} \right) \right) \]

where \( x_0 = \frac{bU_{LG} L}{m_a c_a} \)

5.2.4 Module IV: Semitransparent PV module having air duct above the module

The schematic diagram of semitransparent PV module having duct above PV module is shown in the Figure 4.4. The flowing air gets heated by solar radiation and also from various top and bottom losses. The cross-section view and energy flow diagram of semitransparent PV module having air duct above module is shown in the Figure 5.5 (a) & (b).

Figure 5.5 (a): Cross-section view of semitransparent PV module having air duct above the module
i) For solar cell of PV module:

\[ P_{1GG} + P_{2GG} = P_{3GG} + P_{4GG} + P_{5GG} \]  \hspace{1cm} (5.4 a)

\[ P_{1GG} = \tau_g^2 \alpha_c^2 I(t) \beta_c b d_x \] = rate of solar energy received by solar cell after transmission.

\[ P_{2GG} = \tau_g^3 (1-\beta_c) \alpha_b I(t) b d_x \] = rate of solar energy available on blackened surface from non packing area of PV module.

![Energy flow diagram](image)

Figure 5.5 (b): Energy flow diagram

\[ P_{3GG} = U_{tGG} (T_c - T_{air}) b d_x \] = rate of heat loss from solar cell to air

\[ P_{4GG} = U_{bGG} (T_c - T_a) b d_x \] = rate of heat loss from solar cell to ambient

\[ P_{5GG} = \eta_c \beta_c I(t) \alpha_c^2 \tau_g^2 b d_x \] = rate of electrical energy produced

ii) For air flowing through the duct:

\[ P_{3GG} = P_{6GG} + P_{7GG} \]  \hspace{1cm} (5.4 b)

\[ P_{6GG} = m_a c_a \frac{dT_{air}}{dx} dx \] = heat carried away with flowing air
\[ P_{7GG} = h_{1GG} (T_\text{air} - T_a) bd \ \text{x} \]  
rate of heat loss from flowing air to ambient

With the help of above Eqs., solar cell temperature expression can be written as:

\[ T_c = \frac{\left( \tau_g \omega c \alpha c^2 + \tau_g \frac{3}{2} \alpha_b (1-\beta_c) - \tau_g \omega c \beta c \alpha c^2 \right) I(t) + U_{bGG} T_a + U_{tGG} T_\text{air}}{U_{tGG} + U_{bGG}} \]

(5.4 c)

Substituting the values from Eqn. (5.4 a) and (5.4 c) in Eqn. (5.4 b) and rearranging them, we get

\[
\frac{dT_\text{air}}{dx} + \left( \frac{bU_{LGG}}{m_a c_a} \right) (T_\text{air} - T_a) = \frac{b h \alpha \tau \eta_{eff} I(t)}{m_a c_a} \]

(5.4 d)

Integrating Eqn. (5.4 d) and applying initial condition i.e. \( T_\text{air} = T_\text{airin} \) at \( x=0 \), temperature of air flowing inside air duct can thus be obtained as:

\[
T_\text{air} = \left[ T_a + \frac{h \alpha \eta_{eff} I(t)}{U_{LGG}} \right] \times \left[ 1 - e^{-\frac{bU_{LGG} x}{m_a c_a}} \right] + T_\text{airin} e^{-\frac{bU_{LGG} x}{m_a c_a}} \]

(5.4 e)

Outlet air temperature over complete length of duct is given by:

\[
T_\text{airout} = \frac{1}{L} \int_0^L T_\text{air} \ dx
\]

\[
T_\text{airout} = \left[ T_a + \frac{h \alpha \eta_{eff} I(t)}{U_{LGG}} \right] \times \left[ 1 - e^{-\frac{bU_{LGG} L}{m_a c_a}} \right] + T_\text{airin} \left[ 1 - e^{-\frac{bU_{LGG} L}{m_a c_a}} \right] \]

(5.4 f)

At long last solar cell temperature for given atmosphere parameters can be effortlessly gotten. The rate of productive warm energy can be gotten by putting the qualities in Eqn. (1.7 f) and accordingly can be acquired as:
The temperature dependent electrical efficiency from Eqn. (1.6) can thus be obtained as:

$$
\eta_{el} = \eta_0 \frac{1 - \frac{\beta_0 (\alpha \tau) \text{eff} I(t)}{U_{tGG} + U_{bGG}}}{1 - \eta_0 \beta_0 x_0^2 \frac{2 \alpha_c^2 \beta_c}{U_{tGG} + U_{bGG}}} \left( 1 + \frac{U_{tGG} h_{pLGG}}{U_{LGG}} \frac{1 - \frac{1 - \exp(-x_0)}{x_0}}{\frac{1 - \exp(-x_0)}{x_0}} \right) \tag{5.4 h}
$$

Here, $x_0 = \frac{bU_{LGG} L}{m'a_c a}$

If $N$ numbers of collectors are connected in series then the temperature of outlet air from $N^{th}$ hybrid PV/T module can be written as:

$$
T_{airoutN} = T_a + \frac{(\alpha \tau) \text{eff} I(t)}{U_L} \times \left\{ 1 - e^{-\frac{-N bU_{LGG} L}{m'a_c a}} \right\} + T_{airin} e^{-\frac{-N bU_{LGG} L}{m'a_c a}} \tag{5.5}
$$

If all $N$ set of hybrid PV/T module are identical then the expression for useful heat gain can be derived as:

$$
Q'_{\text{thermalN}} = NAF_R \left( 1 - \left( \frac{1 - K K}{NK} \right)^N \right) (\alpha \tau) \text{eff} I(t) - U_L \left( T_{airin} - T_a \right) \tag{5.6}
$$

Where $K_K = \frac{bU_{LGG} F_R}{m'a_c a}$

5.2.5 Solar dryer partially covered with PV module:

5.2.5.1 System description

The proposed model of solar dryer has been designed for the purpose of
The major component of solar dryer is solar air heater and drying unit. The solar air heater part consists of a PV module and a glass as flat plate collector. The design of hybrid PVT solar dryer is shown in the Figure 5.6 (a) and its cross-section view is shown in the Figure 5.6 (b).

The incoming solar radiation fall on PV module which converts solar radiation into electricity which is used to drive a DC fan for forced mode of operation. The function of collector is to convert solar radiation in the form of solar energy. A 12 V DC fan which is used to extract the heated air is connected at the outlet of air heater. This heated air is then forced into the drying chamber which then passes through number of meshes which consist of trays in which required crop material for drying can be placed. This air then takes away the moisture content of the drying material and get exhausted through chimney. The sides of the drying chamber are sealed properly with putty in order to avoid any leakage of air. To face the problem of rain water drainage in rainy season, a slanting roof was provided above the drying chamber.

5.2.5.2 Thermal analysis of solar dryer

The energy balance equations of solar dryer partially covered with PV module can be written by following the same assumptions as given in the section 5.2. The energy balance equations can be written as:

i) For solar cell

\[
\tau_g \alpha_c \beta_c I(t) \text{bd}_x = U_{c,a}(T_c - T_a) \text{bd}_x + U_{c,air}(T_c - T_{air}) \text{bd}_x + \alpha_c \eta_c \beta_c I(t) \tau_g \text{bd}_x
\]

\[
\tau_g \alpha_c \beta_c I(t) \text{bd}_x = \text{rate of solar energy available on solar cell}
\]
Figure 5.6 (a): Schematic diagram of hybrid PVT solar dryer

Figure 5.6 (b): Cross-section view of solar dryer partially covered with PV module
$U_{tc,a} (T_c - T_a) bd_x =$ an overall heat loss from top surface of the solar cell to the ambient

$U_{Tc,air} (T_c - T_{air}) bd_x =$ an overall heat loss from solar cell to the flowing air

$\alpha_c \eta_c \beta_c I(t) \tau_g bd_x =$ rate of electrical energy produced

From Eqn. (5.7), the temperature of the solar cell can be obtained as-

$$T_c = \frac{(\alpha \tau)_1, eff I(t) + U_{tc,a} T_a + U_{Tc,air} T_{air}}{U_{tc,a} + U_{Tc,air}} \quad (5.7 \text{ a})$$

ii) For blackened absorber plate

$$\alpha_b \tau_g^2 (1 - \beta_c) I(t) bd_x = h_{p,air} (T_p - T_{air}) bd_x + U_{bp,a} (T_p - T_a) bd_x \quad (5.8)$$

$\alpha_b \tau_g^2 (1 - \beta_c) I(t) bd_x =$ rate of solar energy available on blackened surface

$h_{p,air} (T_p - T_{air}) bd_x =$ rate of heat transfer from blackened plate to flowing air

$U_{bp,a} (T_p - T_a) bd_x =$ an overall heat loss from blackened plate to ambient

An expression for temperature of blackened absorber plate can be obtained as-

$$T_p = \frac{(\alpha \tau)_2, eff I(t) + U_{bp,a} T_a + h_{p,air} T_{air}}{U_{bp,a} + h_{p,air}} \quad (5.8 \text{ a})$$

iii) For Air flowing through the duct

$$m_a c_a \frac{dT_{air}}{dx} dx = h_{p,air} (T_p - T_{air}) bd_x + U_{Tc,air} (T_c - T_{air}) bd_x \quad (5.9)$$
\[
m_a \cdot c_a \frac{dT_{\text{air}}}{dx} = \text{mass flow rate of flowing air}
\]

\[
h_{p,\text{air}} \left( T_P - T_{\text{air}} \right) \, bd = \text{rate of heat transfer from blackened plate to flowing air}
\]

\[
U_{Tc,\text{air}} \left( T_c - T_{\text{air}} \right) \, bd = \text{an overall heat loss from solar cell to the flowing air}
\]

Solving Eqn. (5.9) with the help of Eqs. (5.7 a) & (5.8 a) and rearranging them, we get

\[
\frac{dT_{\text{air}}}{dx} + \left( \frac{bU_{L,m}}{m_a c_a} \right) (T_{\text{air}} - T_a) = \frac{b(\alpha \tau)_{m,\text{eff}} I(t)}{m_a c_a}
\]

(5.10)

Integrating Eqn. (5.10) with initial condition \( T_{\text{air}} = T_{\text{air in}} \) at \( x=0 \) and at \( x=L \),

\[
T_{\text{air}} = T_{\text{air out 1}} , \text{ outlet air temperature from the PV module can be obtained as-}
\]

\[
T_{\text{air out 1}} = T_a + \left( \frac{(\alpha \tau)_{m,\text{eff}} I(t)}{U_{L,m}} \right) \times \left( 1 - e^{-\frac{-bU_{L,m} L}{m_a c_a}} \right) + T_{\text{air in}} e^{-\frac{-bU_{L,m} L}{m_a c_a}}
\]

(5.10 a)

Rate of thermal energy accessible at the end of collectors-

\[
Q_{\text{thermal,m}} = m_a c_a (T_{\text{air out}} - T_{\text{air in}})
\]

(5.11)

Substituting the value of \( T_{\text{air out}} \) from Eqn. (5.10 a), we get

\[
Q_{\text{thermal,m}} = A_m F_{Rm} \left[ (\alpha \tau)_{m,\text{eff}} I(t) - U_{L,m} (T_{\text{air in}} - T_a) \right]
\]

(5.12)

Outlet from the PV module-collector ( \( T_{\text{air out}} \) ) is given as inlet to the glass-collector ( \( T_{\text{air in}} \) ). The final outlet air temperature \( T_{\text{air out}} \) from PVT air collector can be obtained as –
Here again $T_{\text{airin}} = T_{\text{airout}}$, the expression for outlet air temperature from PVT air collector reduces to-

$$T_{\text{airout}} = T_a + \left( \frac{(\alpha T)_{\text{c,eff}} I(t)}{U_{L,c}} \right) \times \left\{ \frac{-bU_{L,c} L}{m_a c_a} \right\} + \frac{-bU_{L,m} L}{m_a c_a} \left( 1 - e^{\frac{-bU_{L,m} L}{m_a c_a}} \right) \tag{5.13}$$

Rate of thermal energy available from hybrid PV/T solar dryer can be written as-

$$Q_{\text{thermal}(m+c)} = m_a c_a \left( T_{\text{airout}} - T_{\text{airin}} \right) \tag{5.14}$$

Substituting the values in above Eqn we get

$$Q_{\text{thermal}(m+c)} = A_m F R_m \left[ (\alpha T)_{m,\text{eff}} I(t) - U_{L,m} (T_{\text{airin}} - T_a) \right] + A_c F_{Rc} \left[ (\alpha T)_{c,\text{eff}} I(t) - U_{L,c} (T_{\text{airout}} - T_a) \right] \tag{5.14a}$$

$$T_{\text{airout}} = T_{\text{airin}} + \frac{Q_{\text{thermal,m}}}{m_a c_a} \tag{5.14 b}$$

Substituting the values and simplifying it, we get

$$Q_{u,\text{thermal}(m+c)} = A_m F R_m \left( \frac{(\alpha T)_{m,\text{eff}}}{m_a c_a} \left( 1 - \frac{A_c F_{Rc} U_{L,c}}{m_a c_a} \right) + A_c F_{Rc} (\alpha T)_{c,\text{eff}} \right) I(t) - A_m F R_m \left( 1 - \frac{A_c F_{Rc} U_{L,c}}{m_a c_a} \right) + A_m F_{Rc} U_{L,c} (T_{\text{airin}} - T_a) \tag{5.15}$$
Instantaneous thermal efficiency expression of flat plate collector can be obtained

$$\eta_i = F_R \left[ (\alpha \tau) - U_L \frac{T_{airin} - T_a}{I(t)} \right]$$

(5.16)

Taking the design parameter of the present case, instantaneous thermal efficiency can be obtained as-

$$\eta_i = 0.62 - 5.12 \frac{T_{airin} - T_a}{I(t)}$$

(5.17)

Table 5.1: Design parameters of hybrid PVT solar dryer

<table>
<thead>
<tr>
<th>Parameters</th>
<th>Values</th>
</tr>
</thead>
<tbody>
<tr>
<td>$A_c$</td>
<td>1.196 m$^2$</td>
</tr>
<tr>
<td>$A_m$</td>
<td>0.364 m$^2$</td>
</tr>
<tr>
<td>$B$</td>
<td>0.65 m</td>
</tr>
<tr>
<td>$C_a$</td>
<td>1005 kJ/kg K</td>
</tr>
<tr>
<td>$F_R$</td>
<td>1</td>
</tr>
<tr>
<td>$L$</td>
<td>2.4 m</td>
</tr>
<tr>
<td>$h_p1$</td>
<td>0.47</td>
</tr>
<tr>
<td>$h_p2$</td>
<td>0.966</td>
</tr>
<tr>
<td>$U_{bp,a}$</td>
<td>0.675 W/m$^2$ K</td>
</tr>
<tr>
<td>$U_{L,C}$</td>
<td>5.9 W/m$^2$ K</td>
</tr>
<tr>
<td>$U_{L,m}$</td>
<td>3.57 W/m$^2$ K</td>
</tr>
<tr>
<td>$U_{tc,a}$</td>
<td>9.6 W/m$^2$ K</td>
</tr>
<tr>
<td>$U_{Tc,air}$</td>
<td>5.6 W/m$^2$ K</td>
</tr>
<tr>
<td>$\alpha_c$</td>
<td>0.9</td>
</tr>
<tr>
<td>$\tau_c$</td>
<td>0.95</td>
</tr>
<tr>
<td>$\beta_c$</td>
<td>0.83</td>
</tr>
<tr>
<td>$\eta_0$</td>
<td>0.12</td>
</tr>
<tr>
<td>$\alpha_b$</td>
<td>0.8</td>
</tr>
<tr>
<td>$T_g$</td>
<td>0.95</td>
</tr>
</tbody>
</table>
5.3 Life cycle cost analysis

5.3.1 Study of embodied energy

Embodied energy concept is now included in the energy calculation of buildings. Embodied energy can be defined by Treolar [128] 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”. Thus the main objective of embodied energy analysis is to calculate the amount of energy required for manufacturing a material or component. This assessment includes the overall energy expanded firstly in order to extract the raw material and secondly in manufacturing of product or component, thirdly in installation and maintaining the component element. For doing the embodied energy investigation of the present PVT system, there needs an evaluation for individual component energy requirement in addition to manufacturing energy needs. The breakup of embodied energy of each constituent of manufacture of PVT air collector is shown in Table 5.2.

Table 5.2: Break up of embodied energy of different component of opaque PV module having duct below module (Agarwal and Tiwari, [92])

<table>
<thead>
<tr>
<th>Sr. No.</th>
<th>Component</th>
<th>Quantity</th>
<th>Energy density (kWh/Kg)</th>
<th>#Total embodied energy (kWh)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>MS support structure</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>(i) Steel angle</td>
<td>10 kg</td>
<td>8.89</td>
<td>88.9</td>
</tr>
<tr>
<td></td>
<td>(ii) Nut &amp; bolt</td>
<td>0.5 kg</td>
<td>8.89</td>
<td>4.44</td>
</tr>
<tr>
<td></td>
<td>(iii) Screw</td>
<td>0.2 kg</td>
<td>8.89</td>
<td>1.78</td>
</tr>
<tr>
<td>2</td>
<td>PVC sheet</td>
<td>1.7 kg</td>
<td>25.64</td>
<td>43.58</td>
</tr>
<tr>
<td>3</td>
<td>Paint</td>
<td>0.4 kg</td>
<td>25.11</td>
<td>10.04</td>
</tr>
</tbody>
</table>
5.3.2 Energy matrices

For computing the performance of various modules of PVT system, there is a need of calculating three basic matrices. These matrices are energy payback time (EPBT), energy production factor (EPF) and LCCE (life cycle conversion efficiency).

5.3.2.1 Energy Payback time (EPBT)

The evaluation of the EPBT primarily depends upon the energy used up in the preparation of material which is used in the fabrication of the system & its component and secondly upon the annual energy yield of the system. By knowing the energy density of different material required in manufacturing, the embodied energy can be calculated.

EPBT can be defined as the entire time necessary to recuperate the total energy required recuperating the total energy used up to arrange the materials used for fabrication of a system. EPBT is also defined as the ratio of aggregate energy expended in the development and altering of the framework ($E_{\text{input}}$) to the total energy accessible at the output.

\[
\text{EPBT(years)} = \frac{E_{\text{input}} \text{ (kWh)}}{E_{\text{output}} \text{ (kWh/year)}}
\]  
(5.18)
5.3.2.2 Energy production factor (EPF)

General execution of PVT framework can be assessed by contrasting the aggregate energy commitment with the aggregate energy generation. The ratio of total energy output to the total energy input is defined as the energy production factor (EPF). As both the energies are function of time, so EPF is itself a function of time. EPF can be evaluated on two basis –

i) On annual basis

\[ \chi_a = \frac{E_{\text{output}}}{E_{\text{input}}} \quad \text{Or} \quad \chi_a = \frac{1}{\text{EPBT}} \]  

If \( \chi_a \rightarrow 1 \) for EPBT=1, the system is meaningful else it is not claim from energy perspective.

ii) On life time basis

\[ \chi_{\text{Life}} = \frac{E_{\text{output}} \times T}{E_{\text{input}}} \]  

(5.18 b)

5.3.2.3 Life cycle conversion efficiency (LCCE)

This is defined as the net energy yield of the system over the life time (T) year’s w.r.t input solar radiation (E_solar)

\[ \varphi_{\text{Life}}(t) = \frac{E_{\text{output}} \times T - E_{\text{input}}}{E_{\text{solar}} \times T} \]  

(5.18 c)

For any system to come in the operating condition, there are a lot of parameters whose costs are to be included like acquiring, operating, maintaining & disposal of a system. All the present value & future value cost are included during a given life time period in order to calculate life cycle cost analysis. There are various costs which must be taken into account in LCCA of the PVT system.
i) Initial costs (Pc)- It is the sum of the costs involved in the system like mild steel support structure cost, PV module costs, DC fan cost, paint cost & fabrication charges.

ii) Operation & maintenance cost- It is the cost that has to be included during the operation phase. For the present study, considering on an average \( R_1, R_2, R_3 \ldots R_n \) is the operation & preservation cost of the PVT system annually then the operation & maintenance cost in terms of present value is given as

\[
P_{o\&M} = R_1 \times \left[ \frac{(1+i)^n - 1}{i(1+i)^n} \right]
\]  
(5.19 a)

iii) Replacement cost- It is characterized as the expense which incorporate the fan and paint and battery substitution cost. The number and timing of capital substitution of the segment of the framework relies on the life of the part and framework. Let \( R_{5,1}, R_{10,2} \) - is the battery substitution expense made at regular intervals and \( R_{10,1}, R_{10,2} \) - is the substitution expense of the fan and paint made in at regular intervals then net substitution cost in term of present quality is given as-

\[
P_{RC} = R_{5,1} \times \left[ \frac{1}{(1+i)^{15}} \right] + R_{10,2} \times \left[ \frac{1}{(1+i)^{10}} \right] + \ldots + R_{10,1} \times \left[ \frac{1}{(1+i)^n} \right] \]

(5.19 b)

iv) Salvage value (Sv)- It is characterized as the expense which incorporates into obliteration and transfer of the framework. On the off chance that ‘Sv ‘is the salvage value toward the end of the framework then net salvage value in term of the present worth is given as-

\[
P_{sal} = S_v \times \left[ \frac{1}{(1+i)^n} \right]
\]  
(5.19 c)

Thus the net present value of the system is given as-

\[NPVL = P_c + P_{O\&M} + P_{RC} - P_{sal}\]

(5.19 d)

By Raman & Tiwari [124], the capital recovery factor over the life time can be expressed as-
CPRF = \frac{i(1+i)^n}{(1+i)^n - 1} \quad (5.19 \, e)

Where \(i\) = rate of interest per year & \(n\) = no. of years.

Table 5.3: Capital cost (Pc), salvage value (Sv) & maintenance cost (Mc) of opaque hybrid PVT module air collector

<table>
<thead>
<tr>
<th>Component</th>
<th>Quantity</th>
<th>PVT air collector Rs</th>
<th>Salavage value(Sv) at the inflation rate of 4% (Present value of scrap for iron @ Rs (15 kg))</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mild steel support structure @ Rs 50 (kg)</td>
<td>10.7 Kg.</td>
<td>535</td>
<td>After 20 year Iron scrap @Rs 33(kg) After 30 year Iron scrap @Rs 49(kg) After 40 year Iron scrap@Rs 72(kg)</td>
</tr>
<tr>
<td>PV module @ Rs5000/75Wp</td>
<td>1 no.</td>
<td>5000</td>
<td>100 100 100</td>
</tr>
<tr>
<td>DC fan(12 V &amp;1.8 A)</td>
<td>1 no.</td>
<td>350</td>
<td>15 15 15</td>
</tr>
<tr>
<td>Paint @ Rs 80(kg)</td>
<td>0.4 kg</td>
<td>32</td>
<td>NA NA NA</td>
</tr>
<tr>
<td>Fabrication charges</td>
<td></td>
<td>500</td>
<td>NA NA NA</td>
</tr>
<tr>
<td>Capital cost</td>
<td></td>
<td>Rs 6417</td>
<td>Rs 468 Rs 639 Rs 885</td>
</tr>
</tbody>
</table>

Operational & maintenance cost=Rs 500/per year
Fan replacement cost & paint=Rs 600/-in every 10 year.
NA-no salvage value.
5.4 Annualized uniform cost

Annualized uniform cost (AUC) by Tiwari [4] is defined as the multiplication of the net present value of the PVT system and capital recovery factor is given by

\[ \text{AUC} = \text{NPVL} \times \text{CPRF} \quad (5.20) \]

The cost of per unit of electricity generated by the PVT system is defined as the relative amount of annualized uniform cost and overall thermal energy or exergy produced by the PVT system.

The different method to calculate life cycle cost of PVT system is shown in Figures (a)-(c)

5.4.1 without considering the effect of EPBT

The computation of life cycle cost of the PVT system can be obtained by conventional cash flow diagram as shown in Figure 5.7 (a)

![Figure 5.7 (a) Conventional cash flow diagram for life cycle cost of PVT system without considering effect of EPBT](image)

Here NPVL can be calculated by the given formula-

\[
\text{NPVL} = P + R_1 \times \left[ \frac{(1+i)^n - 1}{i(1+i)^n} \right]_{i,n} + R_{5.1} \times \left[ \frac{1}{(1+i)^n} \right]_{i,5} + R_{10.2} \times \left[ \frac{1}{(1+i)^n} \right]_{i,10} \\
+ R_{10.1} \times \left[ \frac{1}{(1+i)^n} \right]_{i,10} + \cdots + S \times \left[ \frac{1}{(1+i)^n} \right]_{i,n} + \cdots
\]

(5.20 a)
5.4.2 Considering the effect of EPBT

Here the conventional cash flow diagram can be obtained as shown in figure 5.7 (b).

![Conventional cash flow diagram](image)

Figure 5.7 (b) Conventional cash flow diagram for life cycle cost of PVT system considering effect of EPBT

Here NPVL can be calculated by the given formula

\[
NPVL = P_{\text{EPBT}} = P(1+i)^{\text{EPBT}} + R \times (1+i)^{\text{EPBT}-1} + R + R \times \frac{(1+i)^n - \text{EPBT} - 1}{i(1+i)^n - \text{EPBT}} \\
+ R_{F,10} \times \frac{1}{(1+i)^{10-\text{EPBT}}} + R_{F,20} \times \frac{1}{(1+i)^{20-\text{EPBT}}} \\
+ R_{F,K} \times \frac{1}{(1+i)^{K-\text{EPBT}}} + S_v \times \frac{1}{(1+i)^n - \text{EPBT}}
\]

(5.20 b)

5.4.3 Considering the effect of both EPBT & carbon credit

Here NPVL can be calculated by the given formula

\[
NPVL = P_{0,\text{EPBT}} = (\text{CBC} - R) \times (1+i)^{\text{EPBT}-1} + (\text{CBC} - R) \times \frac{(1+i)^n - \text{EPBT} - 1}{i(1+i)^n - \text{EPBT}} \\
+ R_{F,10} \times \frac{1}{(1+i)^{10-\text{EPBT}}} + R_{F,20} \times \frac{1}{(1+i)^{20-\text{EPBT}}} \\
+ R_{F,K} \times \frac{1}{(1+i)^{K-\text{EPBT}}} + S_v \times \frac{1}{(1+i)^n - \text{EPBT}} - P_c (1+i)^{\text{EPBT}}
\]

(5.20 c)
5.5 Exergoeconomic analysis

Energy, being subject to a conservation law can be neither generated nor consumed. Exergy is expended amid a procedure because of irreversibility and is thusly subject to non conservation law. Thusly, the general parity comparison can be composed as, Rosen and Dincer [99].

Energy Input - Energy output = Energy aggregation  \hspace{1cm} (5.21)
Exergy input - Exergy output- Exergy utilization = Exergy gathering \hspace{1cm} (5.22)

The Energy output terms in Eqs. (5.21) and (5.22) can be isolated into component and waste parts. That is

Energy output= Product energy output+ Waste energy output
also,
Exergy output= Product exergy output+ Waste exergy output

Cost is an expanding, non conserved amount. The general parity comparison can be written for cost as (Rosen and Dincer [99])

Cost input+ Cost generation- Cost output= Cost accumulation \hspace{1cm} (5.23)
Cost generation= Capital cost of equipment+ All other creation and maintenance costs \hspace{1cm} (5.24)

Two types of thermodynamic losses are considered. For convenience, the energy loss for a system is denoted as \( W_{en} \) (loss based on energy) and \( W_{ex} \) (loss based on exergy)
\[ W_{en} = \text{Waste energy output} \]

\[ W_{ex} = \text{Exergy consumption} + \text{Waste exergy output} \]

Capital cost is defined using cost balances in Eqs. (5.23) and (5.24) and is denoted by \( P_c \).

Here \( P_c \) is the capital cost of equipment.

Following Eqs. are used to find out energy and exergy losses (Rosen and Dincer [99])

\[ W_{energy} = \sum \text{Input}_{Energy} - \sum \text{Products}_{Energy} \quad (5.25) \]

\[ W_{exergy} = \sum \text{Input}_{Exergy} - \sum \text{Products}_{Exergy} \quad (5.26) \]

A new parameter \( R_x \) is defined as the ratio of thermodynamic loss rate \( W \) to capital cost \( P_c \) and is given as

\[ R_x = \frac{W}{P_c} \]

Two types of losses are to be considered for analysis purpose i.e \( R_{xen} \) for loss based on energy and \( R_{xex} \) for loss based on exergy.

\[ R_{xen} = \frac{W_{en}}{P_c} \quad (5.27) \]

\[ R_{xex} = \frac{W_{ex}}{P_c} \quad (5.28) \]

### 5.6 Envireoeconomic analysis

#### 5.6.1 on overall thermal energy gain basis

Module I: Opaque PV module having air duct below PV module

Bangalore

Overall thermal energy produced annually 742.18 kWh

If unit cost of electricity is Rs. 6.5 then,

The cost of energy produced per annum = 742.18 x 6.5 = Rs. 4824.17

The amount of CO\(_2\) emission for unit power consumption will be 2.08 x 0.982 = 2.04 kg/kWh

The carbon dioxide reduction per annum = 2.04 x 742.18 = 1514.04 kg
In ton=1.514 t CO$_2$e
In the event that carbon dioxide outflow at present is being exchanged @€23/t CO$_2$e, then cost of carbon emission fall per annum=23x1.514= €34.840
This can be changed over in rupees by duplicating current euro rupee transformation element =34.84x67.54= Rs 2353.09.
Similarly cost of carbon emission reduction per annum for New Delhi, Jodhpur & Srinagar is obtained as Rs.2138.99, Rs. 2303.11& Rs.2081.58

5.6.2 on overall exergy gain basis
Bangalore
Overall exergy gain produced annually 170.12 kWh
If unit cost of electricity is Rs. 6.5 then,
The cost of energy produced per annum =170.12x6.5=Rs.1105.78
The amount of CO$_2$ emission for unit power consumption will be 2.08x0.982=2.04 kg/kWh
The carbon dioxide reduction annually=2.04x170.12=347.04 kg
In ton=0.347t CO$_2$e
In the event that carbon dioxide outflow at present is being exchanged @€23/t CO$_2$e, then cost of carbon emission fall per annum=23x0.347= €7.981
This can be changed over in rupees by duplicating current euro rupee transformation element =7.981x67.54= Rs 539.03
Similarly cost of carbon emission reduction per annum for New Delhi, Jodhpur & Srinagar is obtained as Rs.485.61, Rs. 525.05 & Rs.476.89.