Active heating of greenhouse integrated semitransparent photovoltaic thermal system with series connected semitransparent photovoltaic thermal air collectors

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Abstract. In order to fulfill the demand for energy and food security, an active heating of a controlled environment greenhouse integrated semitransparent photovoltaic thermal (giSPVT) system with N-semitransparent photovoltaic thermal (SPVT) air collector for cold climatic conditions has been analyzed in this paper. The proposed SPVT air collectors are connected in series and integrated with giSPVT. It is used to generate thermal as well as electrical energy to meet the daily requirements of users. Based on the energy balance equation which is a function of design and climatic parameters, an analytical expression for various variable parameters namely plant, room air, and solar cell temperatures have been derived. Numerical computation has been made in Matlab for computing the thermal, electrical, and overall exergy of the proposed system. Based on numerical computation, the following observations have been made:

(i) From a thermal point of view, the packing factor (0.5, 0.8) of the semitransparent PV module plays an important role and it must be optimized for maximum thermal heating.

(ii) The selection of a number of collector N is an important parameter to generate electrical energy as well as thermal heating of giSPVT room air in an optimum way.

Keywords: giSPVT system, PV module, SPVT collector, Packing factor.

Nomenclature

\( A_i \) Glass walls/north roof area of giSPVT system (\( m^2 \)); \( i = 1 \) (east wall), 2 (south wall), 3 (west wall), 4 (north wall), and 5 (north roof)

\( A_j \) Glass walls area of giSPVT system (\( m^2 \)); \( j = 1 \) (east wall), 2 (south wall) and 3 (west wall)

\( A_k \) The walls/base area of underground giSPVT system (\( m^2 \)); \( k = 1 \) (east wall), 2 (south wall), 3 (west wall), 4 (north wall) and 5 (base of water pond)

\( A_{RS} \) Area of south semi-transparent PV module roof of giSPVT system (\( m^2 \))

\( A_p \) The plant surface area (\( m^2 \))

\( b \) Breadth of SPVT air collector (m)

\( C_{p} \) Specific heat of plant/water, (\( J/kg^\circ C \))

\( C_{f} \) Specific heat of air (\( J/kg^\circ C \))

\( E_{thex} \) An overall hourly thermal exergy (\( W/m^2 \))

\( F_m \) Stored plant mass factor

\( h_1 \) Total heat transfer coefficient from plant surface to Un-even CE greenhouse room air of giSPVT system (\( W/m^2^\circ C \))

\( h_{pf} \) Heat transfer coefficient from absorber plate to working fluid (air) (\( W/m^2^\circ C \))

\( I(t) \) Solar radiation received by south semi-transparent PV module roof of giSPVT/SPVT air collector (\( W/m^2 \))

\( I_j \) Solar radiation received by glass walls of giSPVT system (\( W/m^2 \))

\( L \) Length of SPVT air collector (m)

\( M_p \) Mass of plant of uneven giSPVT system (kg)

\( m_{f} \) Mass flow rate of flowing air through SPVT collectors

\( Q_\text{u} \) The hourly thermal energy of plant mass (\( W/m^2 \))

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1 Introduction

Energy and food security have become a challenging job due to increased population and industrialization since World War-II with limited cultivated land. Moreover, energy security also becomes prominent in today’s era where power supply instability is a challenge and dependence on only conventional sources is not a viable solution. Therefore, usage of renewable energy is highly required; mainly solar energy being a prominent and reliable source [1]. The controlled environment greenhouse concept can be used to increase vegetable production in a cold climatic condition with higher yield per unit area [2]. In this case, solar radiation is trapped inside the greenhouse which increases the temperature; one of the basic climatic parameters for fast growth and yield due to the greenhouse effect [3, 4]. Off-grid, GiSPVT is the most feasible solution due to the availability of land in rural areas. On grid, GiSPVT is reliable when the natural sunlight is low. However, the cost of such systems is high. A combined wind and solar power plant with reduced power loss and improved construction cost has been addressed in [5] for on grid system. To enhance the efficiency of panels, a motorized curtain is developed to cover the PV module surface during nights and dust storms. This reduces the impact of condensation and accumulation of soiling that could affect the performance of the PV panels and reduce their efficiencies [6].

There are various greenhouses with respect to their shape namely Quonset, even and uneven shape, and ridge and furrow type (consists of uneven shape), etc reported in the literature [7, 8]. The most popular shape is Quonset which is most suitable for cold climatic conditions due to less heat loss from inside to outside environment [9, 10]. The Quonset-shape greenhouse is also known as a passive greenhouse. However, the Quonset shape has limitations due to its shape. The other most popular shape is an uneven passive greenhouse which can be used in larger areas by using the concept of ridge and furrow. In this case, the transparent photovoltaic module can be integrated into the roof of the ridge and furrow shape of the greenhouse to produce electrical power along with trapping direct solar radiation through a non-packing factor area for photosynthesis as well as thermal heating. Such a system is referred to as GiSPVT system [11]. In composite climatic conditions; one needs cooling of the GiSPVT in summer conditions and hence electrical power is required to operate various cooling devices. So, the ridge and furrow GiSPVT system is most suitable for all climatic conditions. Further, [12] shows the concept of an earth air heat exchanger (EAHE) for thermal

\[ \dot{Q}_{a,\text{ex}} \] The hourly exergy of thermal energy of plant mass (W/m²)
\[ Q_{n,\text{th}} \] The rate of thermal energy from N-SPVT air collector (W/m²)
\[ T_{00} \] Side ground temperature/beneath the plants (°C)
\[ T_{a} \] Ambient air temperature (°C)
\[ T_{c} \] Solar cell temperature of uneven GiSPVT system (°C)
\[ T_{cc} \] Solar cell temperature of SPVT air collector (°C)
\[ T_{f} \] Solar cell temperature of SPVT air collector (°C)
\[ T_{fN} \] The outlet fluid air temperature at Nth SPVT air collector (°C)
\[ T_{p} \] The temperature of plants inside uneven GiSPVT system (°C)
\[ U_{b,cr} \] An overall bottom heat transfer coefficient from back of solar cell uneven GiSPVT room air through glass cover (W/m² °C)
\[ U_{bc,f} \] An overall bottom heat transfer coefficient from back of solar cell uneven GiSPVT flowing air through glass cover of SPVT air collector (W/m² °C)
\[ U_{i} \] An overall bottom heat transfer coefficient from uneven GiSPVT room air to ambient air temperature through window glass cover (W/m² °C)
\[ U_{k} \] An overall bottom heat transfer coefficient from plants of uneven GiSPVT room to ground temperature through RCC walls/base of plants (W/m² °C)
\[ U_{\text{eff}} \] An overall effective top heat transfer coefficient from plants of uneven GiSPVT room to ambient air temperature through semi-transparent PV roof (W/m² °C)
\[ U_{l,ca} \] An overall top heat transfer coefficient from top of solar cell to ambient air through top glass cover of south semi-transparent PV module roof (W/m² °C)
\[ U_{l,c,f} \] An overall bottom heat transfer coefficient from back of solar cell to working fluid (air) through bottom glass cover of SPVT air collector (W/m² °C)

**Greek letters**

\[ \gamma \] Conversion factor of thermal power plant
\[ \tau_{g} \] Transmittivity of glass cover of semi-transparent PV module
\[ \eta_{mi} \] An instantaneous electrical efficiency of PV module
\[ \eta_{0} \] An electrical efficiency of solar cell under standard test condition (STC)
\[ \eta_{c} \] An electrical efficiency of solar cell

The controlled environment greenhouse concept can be used to increase vegetable production in a cold climatic condition with higher yield per unit area [2]. In this case, solar radiation is trapped inside the greenhouse which increases the temperature; one of the basic climatic parameters for fast growth and yield due to the greenhouse effect [3, 4]. Off-grid, GiSPVT is the most feasible solution due to the availability of land in rural areas. On grid, GiSPVT is reliable when the natural sunlight is low. However, the cost of such systems is high. A combined wind and solar power plant with reduced power loss and improved construction cost has been addressed in [5] for on grid system. To enhance the efficiency of panels, a motorized curtain is developed to cover the PV module surface during nights and dust storms. This reduces the impact of condensation and accumulation of soiling that could affect the performance of the PV panels and reduce their efficiencies [6].
heating and cooling of GiSPVT by using earth as a heat source. The use of EAHE increased the overall heating or cooling effect. Thermal air collectors are used to maintain the temperature of the greenhouse [13, 14]. The heat transfer coefficient of air is around four times lower than the heat transfer coefficient of water [15–18]. The integration of GiSPVT with the air collector provides thermal and electrical energy. Active greenhouses often have heating and cooling systems to regulate temperatures. These systems may include heaters, fans, and air conditioning units to ensure a stable and favorable climate for plants.

This paper presents a GiSPVT system with a series of connected N-semitransparent photovoltaic thermal (SPVT) air collectors to create a controlled environment and desired temperature for optimum growth. Integration of air collectors with the GiSPVT system provides additional thermal and electrical power to make the system self-sustained even in harsh cold climatic conditions. It will be referred to as the active GiSPVT system. For \( N = 0 \), act as a passive GiSPVT system. Such active greenhouse systems can be used throughout the year. An analytical expression for the plant, room air, solar cell, and SPVT air collector outlet temperature has been derived as design and climatic parameters for hourly, daily thermal, and electrical power from GiSPVT as well as SPVT air collector. Such analysis for active GiSPVT system has not been performed yet for harsh cold climatic conditions. A comparative analysis of the GiSPVT system with and without collectors has been analyzed to demonstrate the practical contribution towards the realization of the state-of-the-art active GiSPVT. The detailed design equations and simulation results are presented in the following sections.

2 Working principle of active GiSPVT system

The design of the active GiSPVT system consists of two parts namely (a) SPVT air collector and (b) GiSPVT. The brief description of both the parts has been described in the following subsections.

2.1 SPVT air collectors

It is made of a semitransparent photovoltaic (SPV) module placed over a blackened absorber which is insulated from the back of the absorber to reduce thermal losses from the backside as shown in Figure 1a. In this case, the blackened absorber received the direct gain through non-packing area of PV module and indirect gain from back of solar cell through bottom toughen glass of PV module. As the ambient air is passed through the inlet of the SPVT air collector, thermal energy is transferred from the blackened surface to flowing air, heated, and exits from the outlet of the SPVT air collector. The outlet of the first SPVT air collector is allowed to enter the second SPVT air collectors for further heating and it goes up to \( N \)th SPVT air collector. Such SPVT air collectors will be referred to as \( N \)-SPVT air collector connected in series and it will be one panel of SPVT air collector. The design parameters and various heat transfer coefficients of the SPVT air collector are given in Table 1a.

2.2 GiSPVT system

In this case, an uneven shape of the greenhouse is considered. The SPV module has been used as a roof facing south to capture maximum solar radiation to be used as direct gain inside the greenhouse through a non-packing area of the PV module for thermal heating as well as for photosynthesis for plants. Here, there is also indirect gain to the GiSPVT room air and the plant by convection for thermal heating. The details of the design of GiSPVT system have been given by [11]. Table 1b has various designs as well as heat transfer coefficients of the GiSPVT system used for numerical computations.

Figure 1b shows the cross-section view of the active GiSPVT system. The inlet air comes from the top of the GiSPVT system which is fed into the SPVT air collector. The outlet of the SPVT air collector at the \( N \)th collector is fed at the bottom of the GiSPVT system in a forced mode of operation. Due to the forced mode of operation, there is no temperature stratification inside the GiSPVT system.

3 Thermal modeling of active GiSPVT system

The following assumptions have been made for expressing an energy balance of each component of the proposed active GiSPVT system:

Figure 1a. SPVT air collector.

Table 1a. Design parameters of PVT air SPVT collector.

<table>
<thead>
<tr>
<th>Parameter</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>( A_{cm} )</td>
<td>1.07 m²</td>
</tr>
<tr>
<td>( C_f )</td>
<td>1005 J/kg °C</td>
</tr>
<tr>
<td>( h_{pf} )</td>
<td>14.82 W/m² °C</td>
</tr>
<tr>
<td>( \dot{m}_f )</td>
<td>0.02</td>
</tr>
<tr>
<td>( U_{bp,a} )</td>
<td>0.68 W/m² °C</td>
</tr>
<tr>
<td>( U_{Lm} )</td>
<td>3.58 W/m² °C</td>
</tr>
<tr>
<td>( U_{tc,a} )</td>
<td>5.7 W/m² °C</td>
</tr>
<tr>
<td>( U_{tc,f} )</td>
<td>9.5 W/m² °C</td>
</tr>
<tr>
<td>( \alpha_c )</td>
<td>0.9</td>
</tr>
<tr>
<td>( \beta )</td>
<td>0.5, 0.8</td>
</tr>
<tr>
<td>( \eta_o )</td>
<td>0.15</td>
</tr>
</tbody>
</table>
There is no temperature stratification along the height of room air due to forced mode of operation.

The whole system is in quasi-steady state condition.

The heat capacity of each material used in construction of SPVT air collector and GiSPVT system is neglected.

Inclination of south roof and SPVT air collector is same to receive similar amount of solar radiation falling on it.

An average value of solar radiation and ambient air temperature has been considered for 0 to t time s due to quasi-steady state conditions.

The plant heat capacity \((M_pC_p)\) has been considered equal to water heat capacity \((M_wC_w)\) due to more than 95% water content in leaves of vegetables.

The packing factor of semitransparent PV module used in SPVT air collector and GiSPVT system is the same.

### 3.1 Thermal analysis of GiSPVT integrated PVT air collector

Based on the above assumptions and Figures 1 of GiSPVT, the basic energy balance for each component of un-even GiSPVT can be written as:

\[(a)\quad \frac{\partial}{\partial t}(\rho V) = \nabla \cdot (\mathbf{Q}) + \dot{Q}_{net},\]

where \(\mathbf{Q}\) is the heat flux density and \(\dot{Q}_{net}\) is the net heat rate.

\[(b)\quad T_c = \frac{\tau_g \beta (\alpha_c - \eta_0) I(t)}{U_{b,cr}} + \frac{U_{b,cr} T_r}{U_{b,cr} + U_{t,ca}}.\]
The values of electrical efficiency under standard test condition (STC), energy density, and temperature coefficient have been given in Table 1b.

(b) For GiSPVT room air:

The rate of thermal energy available from N-SPVT air collectors \( \dot{Q}_{w,N,th} \) connected in series is fed into the GiSPVT room, hence the energy balance of GiSPVT room air will be written as follows:

\[
\dot{Q}_{w,N,th} + U_{h,cr}(T_c - T_r)A_R + h_1(T_p - T_r)A_P = \sum_{i=1}^{5} A_i U_i(T_r - T_a),
\]

or,

\[
\dot{Q}_{w,N,th} = NA_{cm}F_{RN}\left[\left(\tau_T\right)_{m,eff}I(t) - U_{L,m}(T_h - T_a)\right]
\]

where an expression for the rate of thermal energy available from N-SPVT air collectors \( \dot{Q}_{w,N,th} \) connected in series is given (Appendix A - (A7b)) by

\[
\dot{Q}_{w,N,th} = m_i C_f \left[1 - \exp\left(-\frac{N U_{L,m}A_{cm}}{m_i C_f}\right)\right]
\]

and, 

\[
\tau_T = \frac{A_{sp}}{A_{cm} + A_{sp}}
\]

Substitute the expression for \( \dot{Q}_{w,N,th} \) as

\[
\dot{Q}_{w,N,th} = (UA)_{gm} \left( T_p - T_a \right) - PF_3(\tau_T)_{m,eff} I(t)
\]

or,

\[
h_1(T_p - T_r) = (UA)_{gm} (T_p - T_a) - PF_3(\tau_T)_{m,eff} I(t).
\]

(c) For the plants inside GiSPVT system:

The energy balance for the plant of GiSPVT, Figure 1b, has been written as

\[
\sum_{k=1}^{5} A_k U_k(T_{o0} - T_p) + \tau_5^2(1 - \beta)A_R I(t) + \tau_6^3 \sum_{j=1}^{3} A_j I_j = M_p C_p \frac{dT_p}{dt} + h_1(T_p - T_r)A_P.
\]

where \( \tau_6^3 \sum_{j=1}^{3} A_j I_j = 0 \), if all solar radiation exposed either opaque walls of un-even GiSPVT or insulated glass walls and north roof.

Substitute the expression for \( h_1(T_p - T_r) \) from equations (2d) into (3a), one gets

\[
\sum_{k=1}^{5} A_k U_k(T_{o0} - T_p) + \tau_5^2(1 - \beta)A_R I(t) + \tau_6^3 \sum_{j=1}^{3} A_j I_j = M_p C_p \frac{dT_p}{dt} + \left[(UA)_{gm} (T_p - T_a) - PF_3(\tau_T)_{m,eff} I(t)\right] A_P
\]

or,

\[
M_p C_p \frac{dT_p}{dt} + (UA)_{gm} \left( T_p - T_a \right) - PF_3(\tau_T)_{m,eff} A_P I(t)
\]

Further, we have

\[
h_1(T_p - T_r) = h_1 \left[ T_p - \frac{(UA)_{gm} \left( T_p - T_a \right) - PF_3(\tau_T)_{m,eff} I(t)}{h_1 A_{sp} + U_{i,ral} A_{RS} + \left(UA\right)_{gm}} \right]
\]

or,

\[
h_1(T_p - T_r) = \frac{h_1 \left[ U_{i,ral} A_{RS} + \left(UA\right)_{gm} \right]}{h_1 A_{sp} + U_{i,ral} A_{RS} + \left(UA\right)_{gm}} (T_p - T_a) - h_1 A_{sp} + U_{i,ral} A_{RS} + \left(UA\right)_{gm} (\tau_T)_{m,eff} I(t)
\]

The solution of equation (3b) for 0 to \( t \) time interval with initial condition namely \( T_p = T_{p0} \) at \( t = 0 \) becomes
The daily electrical energy in Wh can be determined as

\[
T_p = \left\{ \frac{\tau_g^2(1 - \beta)A_{RS} + PF_3(\tau)_{g_{\text{eff}}}A_P}{(UA)_{\text{wa}} + \sum^{\frac{3}{2}}_{k=1} A_k U_k} \right\} I(t) \tau_g + \sum^3_{j=1} A_j J_j + T_a \right) + T_a \quad \times (1 - e^{-at}) + T_{pf} e^{-at}.
\]

Further, an average plant temperature will be determined as follows:

**See the equation (3d) bottom of the page**

After knowing an average plant temperature from equations (3d), (1b) and (2c) can be rewritten for an average room air (\(T_r\)) and solar cell (\(T_c\)) as

\[
\bar{T}_r = \frac{(\tau)_{g_{\text{eff}}} I(t) + h_1 A_{SPVT} T_p + U_{\text{ra1}} A_{RS} T_\alpha + (UA)_{\text{gm}} T_a}{h_1 A_{SPVT} + U_{\text{ra1}} A_{RS} + (UA)_{\text{gm}}}
\]

and,

\[
\bar{T}_c = \frac{\tau_b (x_c - \eta_0) I(t) + U_{\text{ic}} T_a + U_{\text{ic}} T_r}{U_{\text{ic}} + U_{\text{ic}}}
\]

### 3.2 Electrical efficiency, power and energy of GiSPVT system

An instantaneous electrical efficiency of PV module of GiSPVT roof will be determined by

\[
\eta_{\text{inj}} = \frac{1}{1 - \beta(\bar{T}_c - 25)}.
\]

The hourly electrical power (W) can be determined as,

\[
\dot{E}_{\text{elgi}} = \eta_{\text{inj}} \times I(t) \times \beta \times A_{RS}(W).
\]

The daily electrical energy in Wh can be determined as

\[
E_{\text{elgi}}(\text{daily}) = \sum \dot{E}_{\text{elgi}}.
\]

### 3.3 Electrical efficiency, power, and energy of N-SPVT air collectors connected in series

The outlet air temperature of N-SPVT air collectors connected in series Appendix A is given by

\[
T_{f_{N}} = \left[ \frac{(\tau)_{\text{eff}} I(t)}{U_{\text{Lm}}} + T_s \right] \left[ 1 - \exp \left( -\frac{NU_{Lm}A_{\text{cm}}}{m_j C_j} \right) \right] + T_l \left[ \exp \left( -\frac{NU_{Lm}A_{\text{cm}}}{m_j C_j} \right) \right].
\]

Here, \(T_R = \bar{T}_r\).

The average fluid temperature of the N-SPVT air collector can be obtained as,

\[
T_{f_{N}} = \frac{T_{f_{N}} + \bar{T}_r}{2}.
\]

After getting an average fluid temperature (\(T_{f_{N}}\)), the solar cell temperature of N-SPVT air collector will be determined by using equation (6c) as

\[
\eta_{\text{inj,co}} = \eta_{\text{inj}} \left[ 1 - \beta(\bar{T}_{cc} - 25) \right].
\]

The hourly electrical power in W can be determined as

\[
E_{\text{inj,co}} = \frac{\eta_{\text{inj,co}} \times I(t) \times \beta \times N \times A_{\text{cm}}(W)}{1000}
\]

The daily electrical energy in Wh can be determined as

\[
E_{\text{inj,co}}(\text{daily}) = \sum \dot{E}_{\text{inj,co}}.
\]

### 3.4 Thermal power of GiSPVT

The rate of thermal energy of GiSPVT can be evaluated as follows:

\[
\dot{q}_{\text{th}} = M_p C_p (T_{p_{t=1}} - T_{r_{t=0}})(W).
\]

### 4 Proposed methodology

The following methodology has been adopted to evaluate various hourly temperatures and electrical efficiency by using Matlab for design parameters given in Table 1 and climatic parameters shown in Figure 2.

**Step 1:** Equation (3d) has been used to determine hourly variation of average plant temperature (\(T_p\)) inside GiSPVT system. After knowing the average plant temperature, equations (4a) and (4b) have been used to evaluate hourly average values of room air (\(T_r\)) and solar cell temperature (\(T_c\)) of GiSPVT system.

**Step 2:** For a known hourly variation of average solar cell temperature (\(T_c\)), equations (5a) and (5b) have been used to get hourly variation of electrical efficiency (\(\eta_{\text{inj,b}}\)) and electrical power (\(E_{\text{elgi}}\)) of GiSPVT system.
Step 3: For a known hourly variation of room air temperature ($T_r$) from step 1 and Figure 3, the outlet air temperature ($T_{o,N}$) from SPVT air collector and the average air temperature ($T_{p,N}$) of SPVT air collector can be determined from equations (6a) to (6b), respectively. For the known average air temperature ($T_{p,N}$) of SPVT air collector, the average solar cell temperature ($T_{cc}$) of SPVT air collector can be determined from equation (6c).

Step 4: For given the hourly average solar cell temperature ($T_{cc}$) of SPVT air collectors from Step 3 and Figure 5, one can determine the hourly electrical efficiency ($\eta_{eli,co}$) and electrical power ($E_{eli,co}$) from equations (7a) to (7b) respectively.

Step 5: Add hourly electrical power ($\dot{E}_{eli}$) of GiSPVT system and ($E_{eli,co}$) of SPVT air collector to evaluate overall electrical power generation by active GiSPVT system.
Results and discussion

By using the design parameters of Table 1 and climatic parameters as shown in Figure 2, simulation has been performed to assess the performance of the proposed system as shown in various Figures 3–9. \( N = 0 \) means, there is no external heating of the GiSPVT system. Hence, acting as a passive GiSPVT while \( N = 30 \) uses 30 series connected collectors and acts as an active GiSPVT system.

Fig. 4a. Hourly variation of solar cell temperature \( (T_c) \) and electrical efficiency \( (\eta_{ini,gi}) \) of GiSPVT system.

Fig. 4b. Hourly variation of average electrical efficiency \( (\eta_{ini,gi}) \) and electrical power \( (\dot{E}_{elgi}) \) of GiSPVT system.

The hourly variation of the plant (Eq. (3c)), room air (Eq. (4a)), and solar cell (Eq. (4b)) temperatures with \( [N = 30, \text{active heating}] \) and without SPVT air collector \( [N = 0, \text{passive GiSPVT system}] \) of GiSPVT is shown in Figure 3. It has been seen that the plant temperature, which is maximum, reaches up to 32 °C, and solar cell temperature, which is minimum, reaches, up to 24 °C. Further, there is a shift of maximum temperature of all variations due to the large heat capacity of the plant as per our expectation.
There is a maximum shift of maxima in the plant temperature at 18 h and a minimum shift of maxima in solar cell temperature at 15–16 h. The integration of the SPVT air collector i.e. active heating of the GiSPVT system increases all hourly variations of temperatures due to additional feeding of thermal energy externally.

The hourly variation of the electrical efficiency of the SPV module (Eq. (5a)) and the average solar cell temperature of GiSPVT (Eq. (4b)) has been shown in Figure 4a. One can observe that the electrical efficiency of the SPV module decreases with the increase of the solar cell temperature of the SPV module as per equation (5a). These results are in accordance with previous results obtained by many researchers. Further, it is to be noted that there is an increase in solar cell temperature of SPV module due to the integration of the SPVT air collector; however, there is a drop in electrical efficiency due to an increase in its temperature as per our expectation. In GiSPVT, the plant and room temperature and packing factor of the SPV module are important in comparison with the solar cell temperature of GiSPVT. Based on the average hourly variation of solar cell temperature in Figure 4a, an average electrical power in kW has been shown in Figure 4b. It is seen that the average electrical power is maximum at noon unlike other temperatures shown in Figure 3 because solar radiation is maximum at noon (Fig. 2). It is about 6 kW.
Figure 5 shows the hourly variation of various temperatures of SPVT air collectors. For \( N = 0 \), there will not be any results except ambient air temperature which has the lowest value as shown in Figure 5. However, hourly variation of outlet fluid temperature (Eq. (6a)) and its average value (Eq. (6b)), average solar cell temperature and its value (Eq. (6c)) have been shown in Figure 5. It can be observed that an average solar cell temperature is higher than the average outlet fluid temperature due to its direct exposure to solar radiation and its value will depend on packing factor of SPV air collector. The highest temperature is due to the low heat capacity of fluid as air.

Figure 6 represents the average hourly solar cell temperature, equation (6c) and average hourly electrical efficiency, equation (7a) of SPVT air collector to determine the average electrical power, equation (7b) produced by SPVT air collectors connected in series. The results have been summarized in Figure 6. The left-hand side axis is for the electrical efficiency of the solar cell of the semi-transparent SPVT air collector, Figure 6a, which has a lower value in
comparison with the electrical efficiency of the GiSPVT system (Fig. 4a) due to significantly higher temperature as expected. $N = 0$ represents the results for the GiSPVT system only. The electrical power from the SPVT air collector for $N = 30$ have been is shown in Figure 6b. One can see that the electrical power generated by the SPVT air collector, Figure 6b is significantly lower than the electrical power from GiSPVT, Figure 4b due to (i) high

Fig. 7b. Hourly variation of (a) electrical efficiency of GiSPVT system and SPVT air collectors and total electrical power, step 5 at $N = 30$.

Fig. 8. Hourly variation of total electrical power/exergy and thermal power, equation (8) for GiSPVT ($N = 0$) and active GiSPVT ($N = 30$).
operating temperature of the solar cell, Figure 5 and (ii) the number of semi-transparent PV module in SPVT air collector is lower.

The comparison of the electrical efficiency of the SPVT air collector and GiSPVT system has been carried out in Figure 7. This shows that the electrical efficiency of the SPVT air collector is lower than the electrical efficiency of the GiSPVT system due to the high operating temperature of the solar cell, Figure 5 in SPVT air collector as per our expectation. The same figure shows the total electrical power from the SPVT air collector as well as the GiSPVT system which is maximum at noon time and gives about 7 kW.

The thermal energy with \((N = 30)\) means an active GiSPVT system and without SPVT air collector \((N = 0)\) has been shown in Figure 8. Further, electrical power with and without SPVT air collector has also been shown in the same figure and it is observed that there is marginal effect of SPVT air collector on total electrical power. It may be due to a low number of semitransparent PV modules used in SPVT air collectors as desired.
The effect of packing factor on hourly variation of room air temperature of GiSPVT and total electrical power has been shown in Figure 9. It is clear that as the packing factor of the SPVT air collector decreases, hourly variation of room air temperature increases as shown in Figure 9a. However, the hourly electrical power of the SPVT air collector also decreases. As can be seen from Figure 9b, there is an increase in the total electrical power of the GiSPVT system with an increase in packing factor as explained earlier. In this way, the use of the SPVT air collector is to increase the room air temperature of the GiSPVT system, Figure 9a.

6 Conclusions

The electrical and thermal energy of the active GiSPVT system along with an hourly variation of solar cell, room air, and plant temperature has been presented. The trends of results clearly show that active GiSPVT has strong potential to be used in the agricultural system. It has been shown that the electrical efficiency of the SPVT air collector (Fig. 6b) is lower than the electrical efficiency of the GiSPVT system (Fig. 4a) due to the high operating temperature and is clearly in line with the design equation. It has been observed that

(i) There is improvement in room air temperature of GiSPVT due to integration of SPVT air collectors connected in series (Fig. 3).

(ii) There is significant effect of packing factor (0.5, 0.8) on GiSPVT hourly room air temperature. Therefore, these two parameters may be optimized for a specific application to control temperature inside the structure.

On the whole, the proposed design is very simple and may be used to control the environment inside the structure; thereby making it much better than the existing GiSPVT system for overall electrical and thermal power generation.

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References

Appendix A

A1 Basic energy balance equations

(a) For semitransparent PV module

The energy balance equation in terms of $W$ for solar cells of semitransparent PV module has been written as,
\[ \tau_c \alpha \beta_c I(t) \, \text{d}x = \left[ U_{tca}(T_{cc} - T_o) + U_{tcf}(T_{cc} - T_j) \right] \, \text{d}x + \tau_f \alpha \beta_c I(t) \, \text{d}x. \]  

From above equation, one has,
\[ T_{cc} = \frac{\tau_c \alpha \beta_c (1 - \eta_c) I(t) + U_{tca} T_a + U_{tcf} T_j}{U_{tca} + U_{tcf}}. \]  

(b) For blackened absorber plate

Energy balance can also be expressed in terms of $W$ as
\[ \tau_p (1 - \beta_p) T^2 (t) \, \text{d}x = \left[ h_{p,f} (T_p - T_j) + U_{b,a}(T_p - T_o) \right] \, \text{d}x. \]  

Further, the above equation can be rewritten as
\[ T_p = \frac{\tau_p (1 - \beta_p) T^2 (t) + h_{p,f} T_j + U_{b,a} T_a}{U_{b,a} + h_{p,f}}. \]  

(c) For flowing fluid through the air duct

In this case, the rate of thermal energy carried away by fluid in $W$ is given by
\[ \dot{m}_f C_f \frac{dT_f}{dx} = \left\{ h_{p,f} (T_p - T_j) + U_{tca}(T_{cc} - T_j) \right\} \, \text{d}x. \]  

From equations (A1b) to (A2b), one can obtained
\[ U_{tca}(T_{cc} - T_j) = U_{tca} \left[ \frac{\tau_c \alpha \beta_c (1 - \eta_c) I(t) + U_{tca} T_a + U_{tcf} (T_j - T_c)}{U_{tca} + U_{tcf}} \right] \]
\[ = \frac{U_{tca} \tau_c \alpha \beta_c (1 - \eta_c) I(t) - U_{tca} U_{tcf} (T_j - T_c)}{U_{tca} + U_{tcf}} \]
\[ = \left[ h_{p,t} \tau_p \alpha \beta_p (1 - \eta_p) I(t) - U_{tca}(T_j - T_a) \right] \]  

and,
\[ h_{p,f} (T_p - T_j) = h_{p,f} \left[ \frac{\tau_p (1 - \beta_p) T^2 (t) + h_{p,f} T_j + U_{b,a} T_a}{U_{b,a} + h_{p,f}} - T_j \right] \]
\[ = \frac{h_{p,f} \tau_p (1 - \beta_p) T^2 (t) - h_{p,f} U_{b,a} + h_{p,f} (T_j - T_a)}{U_{b,a} + h_{p,f}} \]
\[ = \left[ h_{p,f} \tau_p (1 - \beta_p) T^2 (t) - U_{b,a}(T_j - T_a) \right]. \]

With help of equations (A3a) and (A3b), it can be rewritten as follows:
\[ \dot{m}_f C_f \frac{dT_f}{dx} = \left\{ h_{p,t} \tau_p (1 - \beta_p) T^2 (t) - U_{b,a}(T_j - T_a) \right\} \]
\[ + \left\{ h_{p,f} \tau_p \alpha \beta_p (1 - \eta_p) I(t) - U_{tca}(T_j - T_a) \right\} \, \text{d}x \]
\[ = \left[ (\tau_p m_{eff}) I(t) - U_{l,m}(T_j - T_a) \right] \, \text{d}x \]  

or,
\[ \frac{dT_f}{dx} + b U_{l,m} T_f = \frac{b U_{l,m}}{\dot{m}_f C_f} \left[ (\tau_p m_{eff}) I(t) - T_a \right]. \]  

The solution of equation (A3d) with initial condition of $T_f = T_{p0}$ at $x = 0$ will be obtained as
\[ T_f = \left[ \left( \frac{(\tau_p m_{eff}) I(t)}{U_{l,m}} + T_a \right) - \exp \left( \frac{-b U_{l,m} x}{\dot{m}_f C_f} \right) \right] \]
\[ + T_{p0} \exp \left( \frac{-b U_{l,m} x}{\dot{m}_f C_f} \right). \]  

where, $(\tau_p m_{eff}) = [h_{p,t} \tau_p \alpha \beta_p (1 - \eta_p) + h_{p,f} \tau_p (1 - \beta_p)]$ and
\[ U_{l,m} = U_{tca} + U_{tcf}. \]
\[ h_{p,t} = \frac{U_{tca}}{U_{tca} + U_{tcf}}, \]
\[ U_{p,t} = \frac{U_{tca} U_{tcf}}{U_{tca} + U_{tcf}}; \]
\[ h_{p,t} = \frac{h_{p,t}}{U_{b,a} + h_{p,t}}. \]
\[ U_{b,a} = \frac{U_{tca} U_{b,a}}{U_{tca} + U_{b,a}}. \]

A2 Analytical expression for fluid temperature at outlet of N-SPVT air collector

An expression for an outlet fluid temperature at end of first SPVT air collector, $T_f = T_{f0,1}$ at $x = L$, the length of each PVT air collector becomes as
\[ T_{f0,1} = \left[ \left( \frac{(\tau_p m_{eff}) I(t)}{U_{l,m}} + T_a \right) - \exp \left( \frac{-b U_{l,m} A_{cm}}{\dot{m}_f C_f} \right) \right] \]
\[ + T_{p0} \exp \left( \frac{-b U_{l,m} A_{cm}}{\dot{m}_f C_f} \right), \]  

where $A_{cm} = b \times L$, an area of each SPVT air collector.

If the outlet fluid temperature of first SPVT air collector is connected with the inlet of second SPVT air collector, Figure 1, then an expression for an outlet air temperature of second SPVT air collector in terms of outlet air temperature of first can be written as follows:
\[ T_{f0,2} = \left[ \left( \frac{(\tau_p m_{eff}) I(t)}{U_{l,m}} + T_a \right) - \exp \left( \frac{-b U_{l,m} A_{cm}}{\dot{m}_f C_f} \right) \right] \]
\[ + T_{f0,1} \exp \left( \frac{-b U_{l,m} A_{cm}}{\dot{m}_f C_f} \right). \]  

(A5a)
After substituting the expression for $T_{fo,1}$ from equation (A4b) in equation (A5a), one gets an expression for the outlet air temperature at end of second SPVT air collector as

$$T_{fo,2} = \left[ \frac{(\pi \tau)_{m,eff} I(t)}{U_{L,m}} + T_a \right] \left[ 1 - \exp \left( - \frac{2 U_{L,m} A_{cm}}{\bar{m}_f C_f} \right) \right] + T_b \left[ \exp \left( - \frac{2 U_{L,m} A_{cm}}{\bar{m}_f C_f} \right) \right].$$

(A5b)

Similarly, an expression for the outlet air temperature at end of N-SPVT air collector can be written as follows:

$$T_{fo,N} = \left[ \frac{(\pi \tau)_{m,eff} I(t)}{U_{L,m}} + T_a \right] \left[ 1 - \exp \left( - \frac{N U_{L,m} A_{cm}}{\bar{m}_f C_f} \right) \right] + T_b \left[ \exp \left( - \frac{N U_{L,m} A_{cm}}{\bar{m}_f C_f} \right) \right].$$

(A6)

For simplifying we will consider an average value of $T_{fo,N}$ and $T$ as

$$T_{fo} = \frac{T_{fo,N} + T_b}{2}. \quad (A7a)$$

With help of an expression for $T_{fo,N}$ from equation (A6), one gets

$$\dot{Q}_{a,N,th} = \bar{m}_f C_f (T_{fo,N} - T_b)$$

$$= \bar{m}_f C_f \left[ 1 - \exp \left( - \frac{N U_{L,m} A_{cm}}{\bar{m}_f C_f} \right) \right] \left[ \frac{(\pi \tau)_{m,eff} I(t)}{U_{L,m}} - (T_b - T_a) \right]. \quad (A7b)$$

Further,

$$T_{cc} = \frac{\tau g c \beta_c (1 - \eta_c) I(t) + U_{t,c,a} T_a + U_{t,c,f} T_{fo}}{U_{t,c,a} + U_{t,c,f}}. \quad (A8a)$$