Thermal Modeling and Experimental Study of a Hybrid Solar Photovoltaic and Earth Air Heat Exchanger System as an Alternative Energy Source for Greenhouse

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Abstract: Solar photovoltaic (SPV) is one of the technologies, which utilizes the nature's gift (solar energy) in the form of electrical as well as thermal energy. Heating of greenhouse is one of the most energy consuming activities during winter periods. Lack of required heating of surrounding environment inside greenhouse creates the adverse effects on the yield, cultivation time, quality and quantity of the products. The photovoltaic system combined with buried pipe system is a feasible method not only to provide thermal energy obtained from the earth at a certain depth to the greenhouse but also to supply electrical energy for the blower used in the buried pipe system resulting in the indirect way of increasing the over all thermal and electrical efficiency of photovoltaic system. Hence considering the importance of buried pipe system (also called Earth air heat exchanger system; EAHE) as a simple, inexpensive and alternative source of energy, the system has been integrated with photovoltaic system in OUAT, Bhubaneswar, Odisha, India during the whole winter period in the year 2010 with a view to study its thermal performance for heating of the greenhouse through a model, developed, for the composite climate of India. The application of solar energy through photovoltaic system and earth air heat exchanger (EAHE) has been studied with the help of a simplified mathematical model for heating of a greenhouse. In a hybrid photovoltaic thermal (PV/T) system, air is taken as the medium for transport of thermal energy. The temperatures of air inside the greenhouse have been compared from the photovoltaic thermal system without air collector, with air collector (during sun shine hours) and with EAHE (during off sun shine hours) along with the overall efficiency (thermal and electrical) of PV/T system. Numerical computations have been carried out for a typical winter day of composite climate of India. The heating potential of the system is evaluated in terms of coefficient of performance (COP) and thermal load levelling (TLL). The results showed that the required temperature for air inside the greenhouse could be maintained during the winter period and overall efficiency could also be increased if the system is operated with PV/T device (with air collector) during day time and EAHE in night time. The electrical efficiency of a hybrid photovoltaic thermal system with air collector was found to be higher due to low operating temperature. There occurred 7 –8 0C rise of temperatures for greenhouse air during winter period particularly in night time due to the incorporation of EAHE as compared to without EAHE. Also there occurred 6-7 0C decrease of air temperature during day time by use of PV/T system integrated with greenhouse.

Keywords: *Solar energy, Green House, photovoltaic system, Earth air Heat Exchanger, Thermal Modeling.*

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Nomenclature

A- Area (m2); B-Breadth (m); c- Specific heat (J kg-1oC-1); dx- Elemental length (m); Fn-Fraction of solar radiation falling on north wall, dimensionless, decimal; FR -Heat re-moval factor for EAHE from underground earth's surface; h- Convective heat transfer coefficient (Wm-2 oC); hi -Heat transfer coefficient from greenhouse cover to inside green-house air, W/m20C, (2.8 □3.0 v); ho -Heat transfer coefficient from greenhouse cover to ambient,W/m20C,(5.7 □3.8 v); hgf - Convective heat transfer coefficient from underground earth's surface to flowing air inside the buried pipes, W/m20C ; hg□- Heat transfer coeffi-cient from floor to larger depth of ground, W/m20C; hna -Heat transfer coefficient from north brick wall to ambient, W/m20C; hnr -Heat transfer coefficient from north wall to greenhouse air, W/m20C; hgr -Heat transfer coefficient from floor to greenhouse air, W/m20C; hp1- Penalty factor due to presence of solar cell material, tedlar and EVA.; hp2 - Penalty factor due to presence of interface between tedlar and working fluid through ab-sorber plate; H-Constants defined in Eq. (18b); I (t)Incident solar intensity on inclined (Wm^{-2}) ; K- Thermal conductivity (Wm^{-1} °C) L- Length of module (m); ma Mass flow rate of air (kg); M- Mass (kg); N- Number of air changes per hour; qu- Rate of useful thermal energy obtained from photovoltaic system (W); Qh -Heating potential of- fered by EAHE for greenhouse air, J; & Qu Useful thermal energy obtained from EAHE for greenhouse air, W; r -Reflectivity from greenhouse cover, dimensionless, decimal; rg - Reflectivity from greenhouse floor, dimensionless, decimal; rn - Reflectivity from north wall, dimensionless, decimal; r1 - Radius of buried pipe in EAHE, m; T- Temperature (oC) ; t- Time (sec) ; Td -Delivery temperature, 0C; To -Temperature of ground in which pipes are spread in EAHE, 0C; T fi - Temperature of inlet fluid or temperature at suction point, 0C for EAHE; Tsc -Suction temperature, 0C; U-Overall heat transfer coefficient; Ub-Overall heat transfer coefficient from bottom to ambient air (Wm-2 oC); U g -Overall heat

transfer coefficient from greenhouse air to floor, W/m20C; UT- Conductive heat transfer coefficient from solar cell to ambient through top and back surface (Wm-2 oC); (UA) - Overall heat loss from greenhouse, W/ 0C; v-Wind velocity (m sec-1); u-Duct air velocity (m sec-1); V-Volume of green house (m3); Greek Letters, β-Packing factor; τ- Transmissiv-ity; α- Absorptivity; η-Efficiency of solar cell; □-Infinity (at larger depth); Subscripts, a - Ambient; bs-Tedlar back surface; c-Solar cell; e -

East wall of greenhouse; G-Glass; g -Floor of greenhouse; i - Different walls and roofs of greenhouse; n -North wall; r - Greenhouse room; s -South wall; T-Tedlar; nr -North roof; sr - South roof; ww -West wall; eff-Effective; th-Thermal; elth- Thermal equivalent to electrical.

1. Introduction

India receives enormous amount of solar energy on an average of 5 kWh/m2/day for about 300 days in a year. It can be used as thermal energy to produce hot water/ air, to heat indoor space, to dry the industrial and agricultural products etc. It can also be used to con-vert sunlight directly to electricity by photovoltaic (PV) and is now being used for a vari-ety of applications. Hence solar photovoltaic (SPV) is one of the technologies, which util-izes the nature's gift (solar energy) in the form of electrical as well as thermal energy. The carrier of thermal energy associated with the PV module can be air or water. The inte-grated arrangements for utilizing thermal energy as well as electrical energy, with a photovoltaic module are referred to as the hybrid photovoltaic thermal (PV/T) system. The thermal energy obtained from hybrid (PV/T) system is supplied to the greenhouse for heating purpose. Tiwari and Sodha (2006) have studied the thermal performance of a hybrid photovoltaic thermal (PV/T) air collector for New Delhi climatic condition in In- dia.Heating of greenhouse is also one of the most energy consuming activities during win-ter periods. Lack of heating has adverse effects on the yield, cultivation time, quality and quantity of the products in the greenhouse (Santamouris et al., 1994). Efforts to decrease energy consumption have directed the researchers to use alternative energy sources for heating of greenhouse. As solar energy is the ideal source of energy for space heating par-ticularly in the northern hemisphere where it is available sufficiently, efforts to harness solar energy have been accelerated during the last decade as world demand for energy is growing at a faster rate (Saravia et al., 1997). The photovoltaic system combined with buried pipe system is also a feasible method not only to provide thermal energy to the greenhouse but also to supply electrical energy for the blower used in the buried pipe sys-tem resulting in the indirect way of increasing the overall thermal and electrical efficiency of photovoltaic system.

Hence considering the importance of buried pipe system (Earth air heat exchanger system; EAHE) as a simple, inexpensive and alternative source of energy, the system has been integrated with photovoltaic system in Indian Institute Technology, model greenhouse, New Delhi, India during the whole winter period with a view to study its thermal perform-ance for heating of the greenhouse through a model, developed, in the composite climate of New Delhi, India.

2. Methodology

An air was taken as the medium for transport of thermal energy in hybrid PV/T air collec-tor.Sixteen PV modules with each having an effective area of 0.605 m2were connected in series. The panel with effective area of 1.62m ×6.5 m was mounted on a galvanized iron structure with the air duct below the module. The inclination of the iron structure support-ing PV modules could be varied to receive maximum solar intensity and also heat-ing/cooling of the greenhouse as per requirement during winter and summer periods re-spectively. In winter, the inclination of PV/T was kept in such a manner that it closes the gap between duct and roof of the greenhouse to increase the inside temperature of green-house. In summer, the gapwas introduced to lower the inside temperature of greenhouse. There was provision to measure the temperature of the inlet and outlet air by using tem-perature sensors. The fans of capacity 12W each have been provided at the inlet to induce the flow of air below the duct for extracting thermal energy available at the back of PV module. The fans were run by a DC battery (12V and 120Ah) charged by the electrical energy generated from PV system. A part of electrical energy generated was used to oper-ate the fans to be used for forced air circulation inside the duct and supplied to the green-house for heating purpose as shown in Fig. 1.

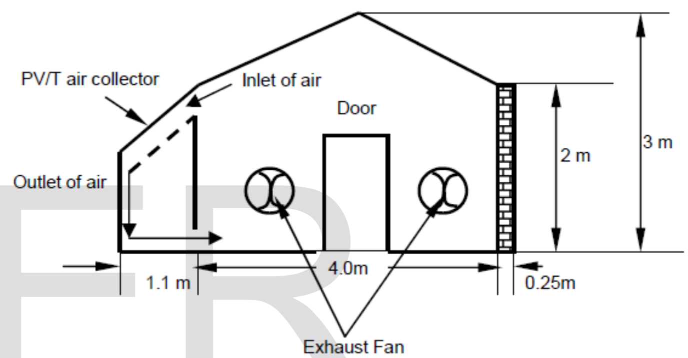

Fig. 1. Front view of PV/T integrated green-

The EAHE under study was installed in the west side of the experimental greenhouse lo-cated in the premises of Indian Institute of Technology, Delhi, India. The climate of the place is composite i.e., it remains hot dry for five months, warm and humid for three months, moderate for one month and cold for three months. The absolute minimum tem-perature of ambient air during winter period is close to 40C while mean minimum is close to 90C. The greenhouse combined with EAHE was of even span type of greenhouse with floor area 6 m x 4 m and was oriented from east to west direction. Total length and diame-ter of buried pipes used were 39 m and 0.06 m respectively. EAHE also consisted of PVC pipes buried under bare surface at the depth of 1 m in a serpentine manner with 8 nos. of turns. The blower was attached in the suction end of the EAHE. The suction and delivery ends of EAHE were placed in the southwest and northwest corners of the greenhouse for allowing uniform mixing of air. The isometric view of experimental greenhouse integrated with photovoltaic system and EAHE is shown in Fig. 2. Experiments were conducted continuously for two days in a week in clear and sunny days from January 2010 to March 2010 and November 2010 to December 2010. However the experimental validation was done for typical date (clear sunny day) of observations i.e., on 23-01-10 for greenhouse arrangement with EAHE, since January is the coldest month. Hourly observations of solar radiation and temperatures of air for ambient condition, greenhouse enclo-

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sure, suction end and delivery end were recorded during the experimentation with the help of calibrated solarimeter and mercury thermometer, respectively. PV panel has been integrated with greenhouse to fulfill the electrical energy demands in the greenhouse. A part of electrical energy generated is used to operate the fans to be used for forced air circulation inside the duct. The rest of electrical energy is utilized for blower of earth air heat exchanger. The specifications of the silicon solar cell at 1000 W/m2 at 25 0C(standard test conditions) used in the PV module were as follows. (i) Fill factor = 0.72; (ii) Short circuit current (Isc) = 4.8 A; (iii) Open circuit voltage (Voc) = 21.7 V; (iv) Area of single solar cell = 0.0139 m2 and

(v) Efficiency of solar cell = 15 %.

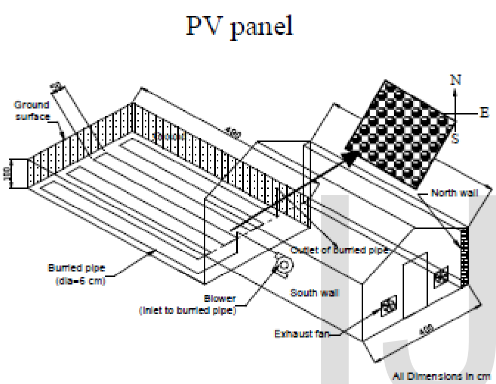

Fig. 2. Isometric view of even span greenhouse integrated with PV/T and EAHE arrangement

2.1 Thermal analysis

Thermal modeling has been carried out for hybrid PV/T air collector and EAHE to find out the outlet air temperature from both the system and then utilization of this useful thermal energy for greenhouse heating during winter season. In order to write an energy balance equations for different components of hybrid photovoltaic air collector the following assumptions have been made:

(i) The system is in quasi steady state condition.
(ii) The transmissivity of EVA is approximately 100%.
(iii) The temperature variation along the thickness as well as along the width is negligible.
(iv) Airflow between the tedlar base and wood structure is uniform for the forced mode of operation and,
(v) The Ohmic losses in solar cells are negligible.

Energy balance for different components of hybrid PV/T air collector can be written as:

1. For PV Module:

$$\tau_G[(\alpha_c I(t)\beta_c)+(1-\beta_c)\alpha_T I(t)]bdx = bdx[\{U_T\{T_c-T_a)+h_T(T_c-T_{bs}\}+\tau_G\eta_c I(t)\beta_c] \quad (1)$$

2. For Back Surface of tedlar:

$$bdxh_T(T_c-T_{bs}) = bdxh_t(T_{bs}-T_{air}), \text{ with air flow} \quad (2a)$$

$$bdxh_T(T_c-T_{bs}) = bdxh_t(T_{bs}-T_r), \text{ without air flow} \quad (2b)$$

3. For air flowing below the tedlar:

$$bdxh_t(T_{bs}-T_{air}) = \dot{m}_a c_a \frac{dT_{air}}{dx}dx + bdxU_b(T_{air}-T_a) \quad (3)$$

$$T_{air} = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff}I(t)}{U_L}+T_a\right]\left[1-e^{\frac{-bU_L}{\dot{m}_a c_a}x}\right]+T_r\left[1-e^{\frac{-bU_L}{\dot{m}_a c_a}x}\right] \quad (4)$$

The outlet air temperature of hot air can be obtained as

$$T_{airout} = T_{air}/x = L = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff}I(t)}{U_L}+T_a\right]\left[1-e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right]+T_r\left[e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right] \quad (5)$$

The average air temperature can be obtained as

$$T_{avg} = \left[\frac{h_{p1}h_{p2}(\alpha\tau)_{eff}I(t)}{U_L}+T_a\right]\left[1-\frac{1-e^{\frac{-bU_L}{\dot{m}_a c_a}L}}{\frac{-bU_L}{\dot{m}_a c_a}}\right]+T_r\left[\frac{1-e^{\frac{-bU_L}{\dot{m}_a c_a}L}}{\frac{-bU_L}{\dot{m}_a c_a}}\right] \quad (6)$$

After knowing an average air temperature, an average solar cell and tedlar back surface (T_{bs}) temperatures can be calculated. The rate of thermal energy obtained from hybrid PV/T air collector with and without airflow is

$$\dot{q}_U = \dot{m}_a c_a(T_{airout}-T_r) = \frac{\dot{m}_a c_a}{U_L}\left\{\left(h_{p1}h_{p2}(\alpha\tau)_{eff}I(t)-U_L(T_r-T_a)\right\}\left[1-e^{\frac{-bU_L}{\dot{m}_a c_a}L}\right], \quad (7)$$

The thermal efficiency of hybrid PV/T air collector is $\eta_{th} = \frac{\sum \dot{q}_U}{\sum I(t)\times b\times L}$ (8)

The temperature dependent electrical efficiency of PV system is

$$\eta_{el} = 1-0.0045(T_c-25) \quad (9)$$

where T_c is the average solar cell temperature. The electrical thermal efficiency can be calculated as $\eta_{elth} = \frac{\eta_{el}}{0.38}$ (10)

The overall efficiency of greenhouse integrated with PV/T system

$$\eta_{ov} = \eta_{th}+\eta_{elth} \quad (11)$$

The useful thermal energy obtained from Eqs. 7 can be used for thermal heating of a greenhouse.

The energy balance equations for various components of greenhouse combined with earth to air heat exchanger can be written on the basis of following assumptions:

(i) Analysis is based on quasi steady state conditions,
(ii) There is no radiative heat exchange between the walls and roofs of greenhouse, due to negligible temperature differences,
(iii) Flow of air is uniform along the length of buried pipes,
(iv) Heat flow is one-dimensional.

Energy balance equations for north wall, floor and room air of greenhouse are as follows:

a) North wall

$$\alpha_n(1-r_n)F_n(1-r)\{\Sigma A_i I_i \tau_i\} = h_{nr}(T|_{y=0}-T_r)A_n + h_{na}(T|_{y=0}-T_a)A_n \quad (12)$$

b) Floor

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\sum A_i I_i \tau_i\} = h_{gr}(T|_{x=0}-T_r)A_g - h_{g\infty}(T|_{x=0}-T_\infty)A_g \quad (13)$$

At larger depths, the temperature of ground is assumed to be equal to ambient air temperature, $T_\infty = T_a$, then Eq. (13) becomes

$$\alpha_g(1-r_g)(1-F_n)(1-r)\{\Sigma A_i I_i \tau_i\} = h_{gr}(T|_{x=0}-T_r)A_g + h_{g\infty}(T|_{x=0}-T_a)A_g \quad (14)$$

c) Greenhouse air

$$h_{nr}(T|_{y=0}-T_r)A_n + h_{gr}(T|_{x=0}-T_r)A_g + \dot{Q}_u = \Sigma A_i U_i(T_r-T_a) + 0.33NV(T_r-T_a) + M_a C_a\frac{dT_r}{dt} \quad (15)$$

The term i.e., $\dot{Q}_u$ in Eq. (15) is the useful thermal energy obtained from earth air heat exchanger arrangement and is expressed by the equation, $\dot{Q}_u = F_R \dot{m}_a C_a(T_0-T_{fi})$ (16)

where $F_R = 1-e^{-\frac{2\pi r_1 h_{gf}}{\dot{m}_a C_a}L'}$ and $T_r = \frac{\overline{B(t)}}{a}(1-e^{-at})+T_{ro}e^{-at}$ (17)

where, T_{ro} is the greenhouse air temperature at $t=0$ and $\overline{B(t)}$ is the average of $B(t)$ for the time interval 0 and t, and a is constant during the time. From Eq. (17), the temperature of air inside greenhouse, combined with earth air heat exchanger can be determined for analysis.

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3. Results and discussion

The energy balance equations derived for greenhouse with photovoltaic system and EAHE have been solved with the help of a computer program based on Matlab software. The closeness of predicted and experimental values has been presented with coefficient of correlation (cr) and root mean square of percent deviation (er). The mass flow rate of the circulating air was kept constant with 100 kg/hour. The performance of EAHE has been evaluated in terms of thermal load leveling (TLL), heating potential and coefficient of performance (COP) as per the following expressions:

$$TLL = \frac{T_{r,\max} - T_{r,\min}}{T_{r,\max} + T_{r,\min}}; \qquad Q_h = \sum \dot{m}_a C_a (T_d - T_{sc}) \Delta t$$

and $$COP = \frac{output\ energy}{Energy\ spent\ to\ get\ output\ energy}.$$

Equation above has been used to calculate solar cell temperature and results are shown in Fig.3. It has been observed that solar cell temperature of photovoltaic/thermal (PV/T) without airflow is higher than the solar cell temperature of hybrid PV/T air collector due to low values of heat transfer from the back surface unlike PV/T air collector. It was also seen that there was rise of around 10^{0}C solar cell temperature of PV/T without airflow. The hourly variation of outlet air temperature is shown in Fig.4. It was observed that outlet air temperature of hybrid PV/T air

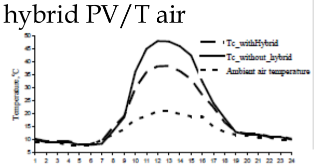

Fig. 3. Hourly variation of solar cell temperature

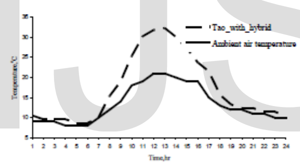

Fig. 4. Hourly variation of outlet air temperature

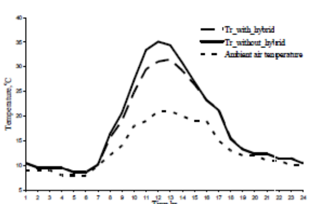

Fig. 5. Hourly variation of greenhouse air temperature

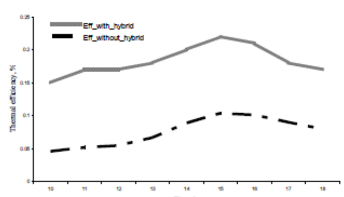

Fig. 6. Hourly variation of thermal efficiency

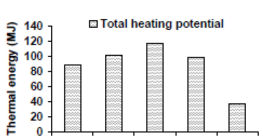

Fig. 7 Monthly variations of total heating potential obtained from EAHE during experimentations

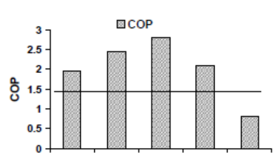

Fig. 8 Monthly variations of coefficient of

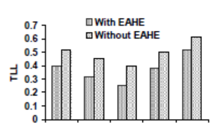

Fig. 9. Monthly variations of thermal load leveling (TLL) during experimentations

nt air temperature and PV/Twithout airflow due to fastheat transferfrom the back surface. Figure 5 shows the hourly variation of greenhouse air temperature. It is concluded that greenhouse air temperature of photovoltaic/thermal (PV/T) without airflow is higher than the room air temperature of hybrid PV/T air collector due to direct transfer of thermal en-ergy from back surface of tedlar to the greenhouse air. Fig. 6 shows the hourly variation of thermal efficiency. It can be concluded that thermal efficiency of hybrid photo-voltaic/thermal (PV/T) air collector is higher than the thermal efficiency of photo-voltaic/thermal (PV/T) without airflow due to low operating temperature. It has also been calculated that thermal efficiency of hybrid photovoltaic/thermal (PV/T) air collector was around 34% and the thermal efficiency of photovoltaic/thermal (PV/T) without airflow was about 8.5%. The performance of EAHE on heating of greenhouse during night time has also been studied with respect to total heating potential, coefficient of performance (COP) and thermal load leveling. PV/T with air flow was used during day time and EAHE was used in night time to enhance the system efficiency.After knowing the suction and delivery temperatures of EAHE as well as mass flow rate, the hourly variations of total heating potential obtained from the system for the typical day in the winter months during night time were calculated and similarly the total heating potentials obtained from EAHE for a typical day in each winter months have been computed and presented in Fig. 7. From the results, it is seen that the heating potentials obtained from EAHE were higher in the month of January followed by December, February, November and March. The higher value of heating potential in January (coldest month) is due to the more differences of temperature in suction and delivery ends. The coefficient of performance determined for typical day in each month has also been presented in Fig. 8 to know the applicability of the system. The values of coefficient of performance were highest in the month of January (2.8), followed by December (2.45), February (2.1) and November (1.94). However, in the month of March, its value was below the dashed line (value less than 1) indicating the system needs to be discontinued during this month. The values of thermal load leveling achieved for typical days in each month have been calculated and presented in Fig. 9 in order to know the efficacy of the system during the study. From the computed results, it was seen that the values of TLL in each month for greenhouse with EAHE were lower than those without EAHE proving the former to be more effective for reducing the fluc-tuations of temperature of air in greenhouse.

4. Conclusions

On the basis of present study, the following conclusions have been made.

- Solar cell temperatures are higher in case of photovoltaic/thermal (PV/T) without airflow due to direct transfer of thermal energy into the greenhouse.
- The temperatures of greenhouse air are higher in the

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case of (PV/T) without airflow due to direct transfer of thermal energy into the greenhouse.

- The thermal efficiency of a hybrid photovoltaic thermal (PV/T) air collector is higher due to low operating temperature.
- There occurred 7 –8 0C rise of temperatures for greenhouse air during winter night time due to incorporation of EAHE compared to without EAHE.
- Decrease of air temperature by 6-7 0C was in day time due to PV/T air collector.
- Relative fluctuations of temperature for greenhouse air are less by use of PV/T air collector in day time and EAHE in night time.

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