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Design, Construction and Testing of Hybrid Photovoltaic Integrated Greenhouse Dryer

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Abstract: In this study, a hybrid Photovoltaic (PV) integrated greenhouse (roof type even span) dryer has been designed and constructed at Solar Energy Park, Indian Institute of Technology (IIT), New Delhi, India. The testing of the proposed hybrid dryer (without load) has been carried out by using the thermal loss efficiency factor. The dryer has floor area of 2.50×2.60 m with 1.80 m central height and 1.05 m side walls height from ground. The roof has slope of 30°. Two PV modules (glass to glass) were used in its construction for thermal heating of greenhouse environment and to provide electrical power to operate a DC fan under forced mode condition. The experiments have been conducted under natural and forced mode operation without load. It has been observed that the direct thermal loss efficiency under forced mode is higher as expected for crop drying. The coefficient of diffusion under natural mode has also been determined.

Key words: Greenhouse dryer, solar energy, PV/T module

INTRODUCTION

One of the applications of greenhouse structures is greenhouse vegetable drying. Products to be dried are placed in trays inside greenhouse for moisture removal either by natural or forced convection. The forced convection greenhouse dryer may be categorized in conventional and PV integrated greenhouse dryer. The conventional greenhouse dryer utilizes grid electricity to operate the fan or blower for forced mode while in PV integrated greenhouse dryer, a DC (direct current) fan is operated by DC electricity produced by PV module.

Condori and Saravia (1998) studied the evaporation rate in two types of forced convection greenhouse driers namely the single and the double chamber systems. The productivity of the double chamber greenhouse drier was increased by 87% for the same drier area in comparison to the single chamber type. Condori and Saravia (2001) has built and tested a low cost forced convection tunnel greenhouse drier. When tunnel greenhouse drier was considered as a solar collector, there was an analytical linear relation between the incident solar radiation and the greenhouse output temperature (Condori and Saravia, 2003). A solar tunnel drier for chilli drying has been optimized in Bangladesh and it is found that the design geometry was not very sensitive to minor material costs, fixed cost and operating cost but more sensitive to costs of major construction materials of the collector, solar radiation and air velocity in the drier (Hossain *et al*., 2005).

Abdullah *et al*. (2001) studied the development of GHE (greenhouse effect) solar drying system from laboratory test to its wider dissemination and found a great potential for its use in rural areas of

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Indonesia. Natural circulation greenhouse solar dryers are 2-5 times more efficient than open sun dryers and the dried product has also better quality than open sun drying (Koyuncu, 2006).Thermal modeling and experimental validation of greenhouse drying system under natural and forced convection mode has been done by various researchers to study the effect of greenhouse on crop drying (Jain and Tiwari, 2004a, b; Kumar and Tiwari, 2006).

The system which can supply electrical and thermal energy simultaneously from a PV module is referred as hybrid photovoltaic/thermal (PV/T) system. A PV/T collector can produce higher output density than a unit PV module or liquid heating flat plate solar collector (Fujisawa and Tani, 1997). An integrated PV/T system is economically feasible (Huang *et al*., 2001).

A thermal model has been developed to evaluate the performance of an integrated photovoltaic and thermal solar (IPVTS) system and experimentally validated. The different configurations (unglazed and glazed, with and without tedlar) of an IPVTS water/air heating system and PV/T air collector has been studied. The characteristic daily efficiency of IPVTS system with water was higher than with air for all configurations except glazed without tedlar case. An overall thermal efficiency for summer and winter conditions was about 65 and 77%, respectively. The performance of glazed hybrid PV/T air collector without tedlar provided was the best. The IPVTS system can be used for various applications namely space heating, water heating, drying, greenhouse, illumination and lighting, etc. (Tiwari and Sodha, 2006a,b).

A very few researchers have used PV module powered air circulation for forced convection drying. PV panel of 20 W was installed separately, from air heater collector and drying chamber, to drive 12 V DC fan of a PV operated forced convection solar energy dryer (Saleh and Sarkar, 2002). A solar dryer was studied with photovoltaic solar cells, incorporated in the solar air heater section, to drive a DC fan. The dryer dried 90 kg maize grain per batch from an initial moisture content of 33.3 to 20% dry basis in just one day. Solar grain drying with a PV-driven DC fan reduces the drying time by over 70% in comparison to sun drying (Mumba, 1995, 1996). Sopian *et al*.(2000) developed and tested a double pass photovoltaic thermal solar collector suitable for solar drying applications.

This study presents the design of a greenhouse dryer, integrated with two PV modules (glass to glass). The PV module produces DC electricity, which may be used to operate a DC fan for removal of the humid air from the greenhouse and at the same time, thermal heat of the PV module is utilized to heat the air inside greenhouse, which will help in drying of crops. The proposed design of PV Integrated Greenhouse Dryer may be one of the most sustainable and attractive choices in remote locations/areas in developing and under developing countries to dry the crops using solar energy, where grid electricity is not readily available.

The testing procedure in terms of thermal loss efficiency factor for such PV integrated greenhouse dryer has been developed.

MATERIALS AND METHODS

Design of Hybrid PV Integrated Greenhouse Dryer

It is having three-tier drying system which may be used for drying of different crops simultaneously. Each tier consists of two wire mesh trays, having base area of 0.9×1.30 m, fitted in centre of greenhouse. The integrated dryer consists of two PV modules (dimensions: 1.20×0.55×0.01 m; 75 Wp) on south roof, two openings (dimension: 1.10×0.55 m) at the north roof symmetrical to PV modules for natural mode operation i.e., for natural convection and an aluminium frame door (size: 0.62×0.88 m) on east side. For forced mode operation, a DC fan (inner diameter = 0.080 m, outer diameter = 0.150 m) has been provided at the top on the east side wall of the dryer (Fig. 1). At bottom side, 0.15 m height is open and further 0.10 m is provided with wire mesh to provide air movement in the greenhouse dryer. The air at bottom becomes hot and moves from bottom to top through three-tier system of perforated wire mesh trays.

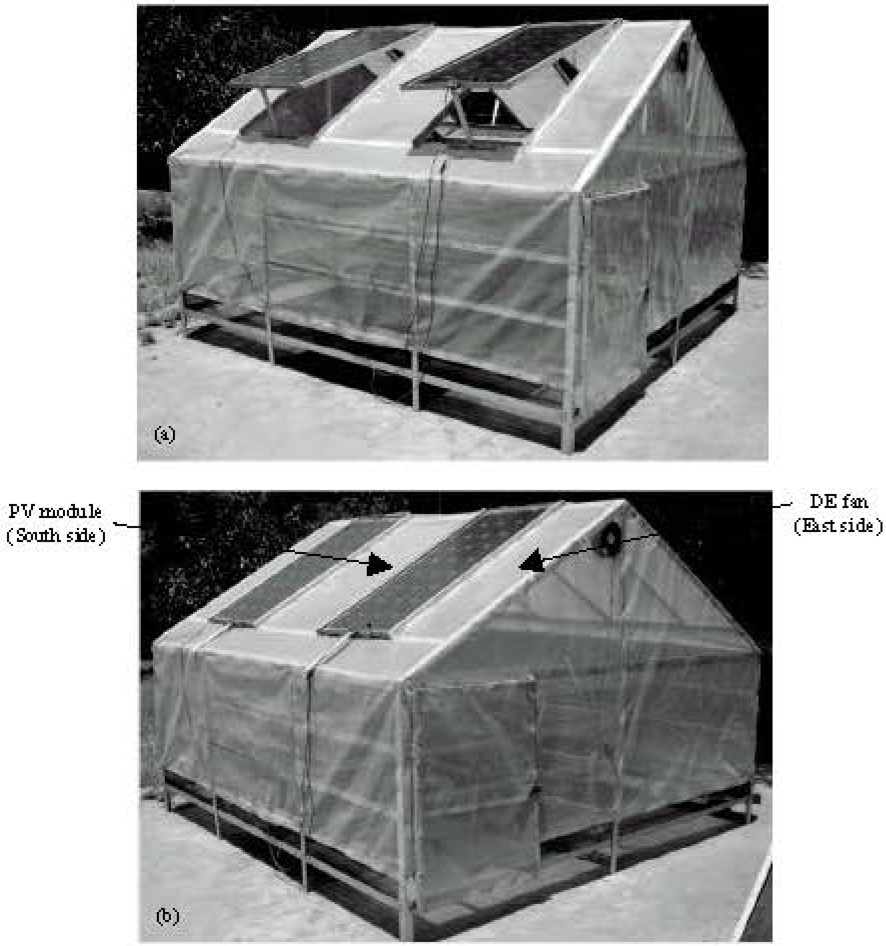

Fig. 1: Experimental set up for (a) natural mode operation (PV Modules raised and DC fan not operated) and (b) forced mode operation (PV Modules not raised and DC fan operated)

The specifications of PV module used for the PV integrated dryer are as follows:

PV Module: Specification at 1000 W m^{-2} at 25°C.

I_{max}	:	4.4 A
V_{max}	:	17 V
Area of module	:	0.60534 m^2
Efficiency	:	12%
Packing factor	:	83%.

Construction of Hybrid PV Integrated Greenhouse Dryer

The dryer was constructed using aluminium sections (e.g., L angles, Tee-sections, flats etc.), two PV modules (glass to glass), a DC fan and UV stabilized polyethylene sheet covering etc. Aluminium sections were used in construction to avoid rusting/corrosion from surroundings and thus to increase the life of the dryer. Wire mesh trays have been made which may be easily taken out and kept in the dryer at specific places. Arrangement for easy opening/closing of PV modules (south side) and symmetrical air vent (north side) has been made using hooks etc. The UV stabilized polyethylene sheet has been fitted over the structural frame of the dryer with the help of steel screws with washer, rivets and nut bolt with washer etc. A DC fan has been fitted at the upper end of the east side wall for rapid removal of humid air and to expedite the drying process to the required level. The orientation of the greenhouse dryer was taken as east-west during experiments.

The experiments were conducted at no-load under natural mode and forced mode operation during the months of May/June, 2006.

Working Principle

The solar radiation, incident on greenhouse, may be divided in following two ways:

Solar Radiation on PV Modules (Glass to Glass)

The incident solar radiation, on glass of PV module (glass to glass), is transmitted to greenhouse to produce heat in the greenhouse or greenhouse effect i.e., increase in greenhouse air temperature.

The incident solar radiation on solar cells of PV module is converted into DC electricity which is used to drive a DC fan for forced mode operation of the dryer i.e., removal of hot and humid air from greenhouse during drying.

The solar cell portion of PV module transfers heat through conduction from front surface of PV module to its back surface. So, the back surface of PV module becomes hot. The hot back surface of PV module transfers heat to greenhouse air through convection. The front surface, facing ambient, loses heat to the atmosphere.

Thus, thermal heat of the PV module is utilized to heat the air inside greenhouse and to provide DC electricity to operate DC fan for forced mode operation.

The temperature of the PV module will reduce as it transfers heat to greenhouse air which will help in drying of crops. It will help in increase of efficiency of PV module also. This is so because with increase in temperature of PV module, its efficiency decreases.

Solar Radiation on UV Stabilized Polyethylene Sheet

The incident solar radiation, on UV stabilized polyethylene sheet, is transmitted to greenhouse to produce heat in the greenhouse or greenhouse effect i.e. increase in greenhouse air temperature. The sheet helps in trapping of infrared radiation and to prevent unnecessary circulation of ambient air which helps in maintaining the desire temperature inside the greenhouse.

Theoretical Considerations

The assumptions made for the study are:

- System is in quasi-steady state.
- The heat capacities of the canopy cover, PV module and greenhouse room air is negligible.
- The effect of shading due to structural members is negligible.
- Edge losses of greenhouse are negligible.
- The thermal loss through ground is negligible.
- Under natural mode, the thermal loss occurs only though canopy cover (including PV module) and vents.

Instantaneous Thermal Loss Efficiency Factor (η_i)

The drying of crops mainly depends on the rate of removal of moisture from the greenhouse. Hence, the drying time of crop will be reduced at faster removal of moisture either by natural or forced mode of operation. This term will be referred as instantaneous thermal loss efficiency factor (η_i) (Sutar and Tiwari, 1996), which is defined as follows:

Under Natural Mode

The rate of instantaneous thermal loss efficiency factor through canopy cover which is indirect loss factor and predominant, can be evaluated as:

$$\eta_{i,canopy} = \frac{\left[U_g(\sum A_i - \sum A_m) + U_m \sum A_m\right](T_r - T_a)}{I(t)A_f} \tag{1a}$$

Further, there will be direct removal of heat (moist air) through vent under natural mode. This direct loss will be defined as instantaneous thermal loss efficiency factor in the term of diffusion coefficient as:

$$\eta_{i,natural} = \frac{C_d n_v A_v \left((2\Delta P)/\rho_r\right)^{1/2} \Delta P}{I(t)A_f} \tag{1b}$$

The testing of PV integrated greenhouse dryer has been carried out under no load condition, then the sum of loss factor due to canopy and vent will be one. By this assumption,

$$\eta_{i,natural} = 1 - \eta_{i,canopy} \tag{2}$$

If $\eta_{i,\ canopy}$ is known, then the coefficient of diffusion (C_d) can be evaluated from Eq. 1b and 2 as

$$C_d = \frac{\left(1 - \eta_{i,canopy}\right)I(t)A_f}{n_v A_v \left((2\Delta P)/\rho_r\right)^{1/2} \Delta P} \tag{3}$$

Under Forced Mode

Under forced mode of operation, the roof vents are closed. In this case, the moist air is removed through a DC fan operated by electrical energy generated by PV module. Under this condition, there will be minimum indirect heat loss through canopy cover i.e.,

$$\eta_{i,\ forced} = \frac{\left[U_g(\sum A_i - \sum A_m) + U_m \sum A_m + 0.33NV\right](T_r - T_a)}{I(t)A_f} \tag{4a}$$

Under forced mode condition, direct loss will be predominant and hence $\eta_{i,\ forced}$ may be written as;

$$\eta_{i,forced} = \frac{0.33NV(T_r - T_a)}{I(t)A_f} \tag{4b}$$

Electrical Efficiency

The electrical efficiency of PV module (glass-to-glass) is given by:

$$\eta_e = \left(\frac{0.8 I_{sc} V_{oc}}{A_m I_p}\right) \times 100 \tag{5}$$

Table 1: Experimental hourly data under forced mode of operation for a typical day (May 26, 2006)

Time (h)	T_a (°C)	γ (decimal)	T_r (°C)	I(t) (W m^{-2})	I_p (W m^{-2})	V_L (V)	I_L (A)	DC fan speed (m sec^{-1})
10:00	31.0	0.388	52.4	296	590	18.1	0.4	4.9
11:00	38.0	0.325	56.6	340	670	17.9	0.4	5.1
12:00	39.0	0.301	53.5	398	690	17.8	0.5	5.0
13:00	40.0	0.281	55.3	384	650	18.0	0.5	5.2
14:00	40.0	0.286	55.4	272	570	17.9	0.4	5.2
15:00	39.0	0.271	56.7	222	440	17.9	0.4	5.1
16:00	38.0	0.304	56.6	148	280	17.5	0.4	4.7

where, T_a = Ambient temperature; ϒ = Relative humidity of ambient air; T_r = Greenhouse room air temperature; I(t) = Total average solar intensity measured inside greenhouse; I_p = Total solar intensity measured normal to PV module surface; V_L = Load voltage and I_L = Load current.

The equivalent thermal efficiency of the PV module is given by

$$\eta_{eth} = \frac{\eta_e}{0.38} \tag{6}$$

The electrical load efficiency is given by

$$\eta_{load} = \left(\frac{I_L V_L}{A_m I_P}\right) \times 100 \tag{7}$$

Instrumentation

A ten-channel digital temperature indicator with least count of 0.1°C (accuracy: ±0.1%) having 9-199°C range with calibrated copper-constant an thermocouples was used to measure the temperature inside greenhouse at different locations. To measure the relative humidity a digital humidity meter (model Luton HT-3003) was used. It had a least count of 0.1% relative humidity with accuracy of ±3% on the full-scale range of 5-99.9% of relative humidity. A Clamp on Multimeter (Tong meter) (least count: 0.1 A and 0.1 V) was used to measure the current and voltage produced by PV module. A Mercury Thermometer (least count 1°C) was used to measure the ambient temperature. A Solarimeter (Make-Central Electronics Ltd., India) was used to measure the solar intensity.

Experimental Observations

The hourly data for solar radiation has been measured at five points inside the greenhouse and the average values of solar intensity have been considered for numerical computation (Appendix). The hourly variation of average solar intensity, intensity on PV modules, ambient air and room air temperatures, relative humidity, load voltage and current and fan speed (forced mode) has been measured for six days in the month of May/June, 2006 (Table 1).

Testing Procedure

The experimental observations were utilized to calculate the thermal loss efficiency factor (η_i) for natural and forced mode conditions without load using Eq. 1a and 4b, respectively (Sutar and Tiwari, 1996). The hourly calculated instantaneous thermal loss efficiency factor (η_i) was plotted against

$$\left(\frac{T_r - T_a}{I(t)}\right).$$

This curve will be referred as thermal loss characteristic curve for proposed greenhouse dryer.

RESULTS AND DISCUSSION

From Fig. 2-4, it is observed that the intercept of all characteristic curve are zero which are in accordance with the results predicted by Sutar and Tiwari (1996). Figure 2 shows the direct loss (through fan) characteristic curve while Fig. 3 and 4 show the indirect loss (through canopy cover)

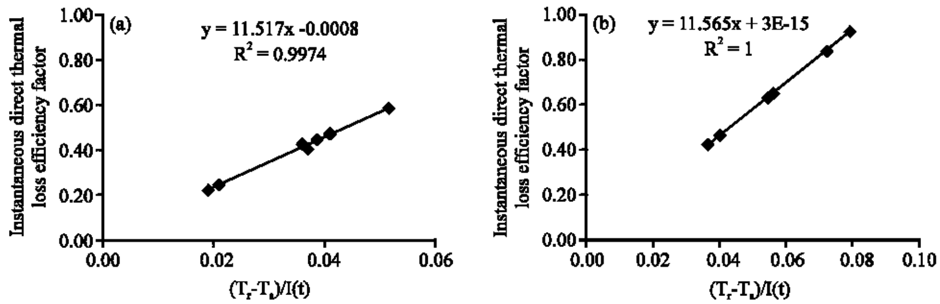

Fig. 2: Variation of η_i with $\left(\frac{T_r - T_a}{I(t)}\right)$ under forced mode for May (a) 22 and (b) 26, 2006

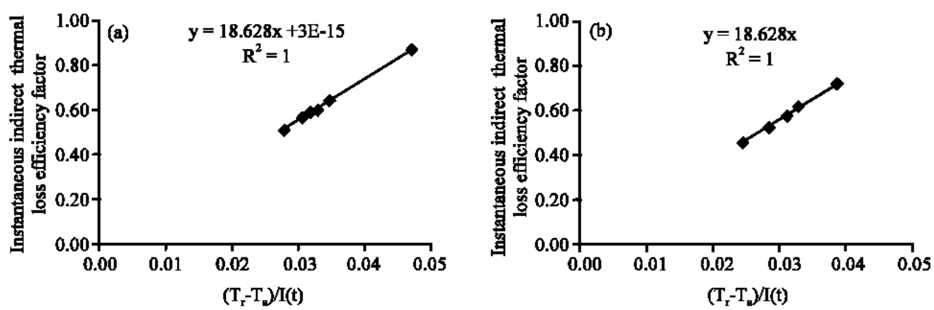

Fig. 3: Variation of η_i with $\left(\frac{T_r - T_a}{I(t)}\right)$ under natural mode when two vents open for June (a) 07 and (b) 09, 2006

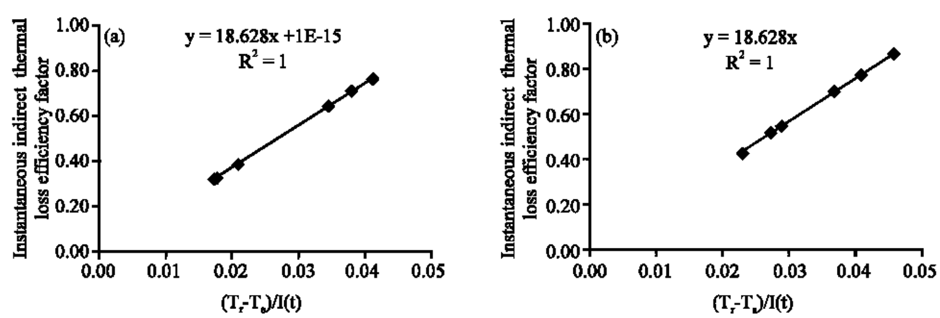

Fig. 4: Variation of η_i with $\left(\frac{T_r - T_a}{I(t)}\right)$ under natural mode when four vents open for (a) May 29 and (b) June 06, 2006

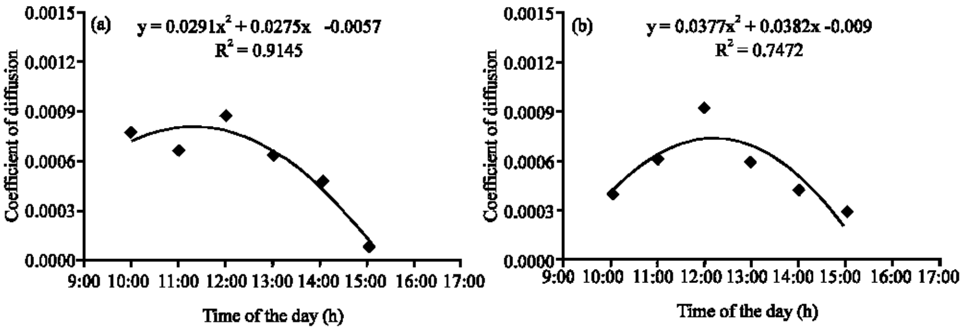

Fig. 5: Variation of coefficient of diffusion (C_d) with time of the day under natural mode when two vents open for June (a) 07 and (b) 09, 2006

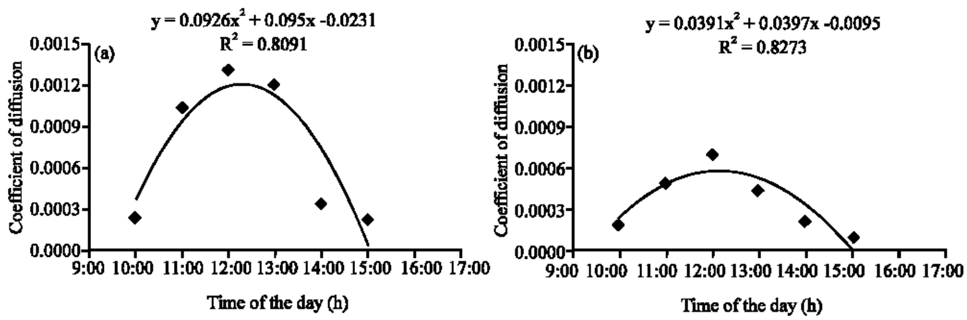

Fig. 6: Variation of coefficient of diffusion (C_d) with time of the day under natural mode when four vents open for (a) May 29 and (b) June 06, 2006

characteristic curve. It is further to be noted that the direct thermal loss under forced mode (Fig. 2), is very large in comparison with direct loss in natural mode of operation hence forced mode drying is an appropriate drying technique as suggested by various scientists (Sodha *et al*., 1987; Jain and Tiwari, 2004a).

Equation 3 has been used to evaluate coefficient of diffusion under different openings. The variation of coefficient of diffusion (C_d) with time of the day under natural mode, for two and four vents open, have been shown in Fig. 5, 6, respectively. It was observed that the value of C_d increases during forenoon, being maximum around at noon and then decreases during afternoon onwards as expected.

The electrical load efficiency was calculated using Eq. 7 and its average value was 2.2- 2.5%. The electrical efficiency of PV module (glass-to-glass) was calculated using Eq. 5 and its average value was 10.8%. The equivalent thermal efficiency of the PV module (glass-to-glass) was calculated using Eq. 6 and its average value was 28.4%. The average available energy from PV modules ($0.8I_{sc}\ V_{oc}$) was 84 W. The calculated electrical load ($I_L\ V_L$) for forced mode operation (one DC fan) was 7-8 W. So there was surplus energy available which may be either utilized for other purposes or suitable for larger size of greenhouse dryer.

CONCLUSIONS

On the basis of the experimental results obtained in this study, the following conclusions may be drawn for integrated hybrid greenhouse dryer:

- An integrated proposed hybrid greenhouse dryer is most appropriate dryer for drying purpose in rural area of under developing countries for sustainable development.
- An excess electrical output can be used for other agricultural activities e.g., water pumping/irrigation etc.
- A thermal loss efficiency of integrated hybrid greenhouse dryer is up to 80% which is similar to gain efficiency of flat plate collectors (Duffie and Beckman, 1991). This indicates the effectiveness of drying process.

Nomenclature

A_f	:	Greenhouse floor area (m^2).
ΣA_i	:	Total surface area of greenhouse including PV module (m^2).
A_m	:	Area of a PV module (m^2).
ΣA_m	:	Area of all PV modules, (m^2).
A_v	:	Vent area (m^2).
C_d	:	Coefficient of diffusion.
DC	:	Direct current.
I_L	:	Load current (A).
I_p	:	Total solar intensity measured normal to PV module surface (W m^{-2}).
I_{sc}	:	Short circuit current (A).
I(t)	:	Total average solar intensity measured inside greenhouse (W m^{-2}).
N	:	Number of air changes per hour from DC exhaust fan.
n_v	:	Number of vents used.
P(T)	:	Partial vapour pressure of moist air at temperature T (N m^{-2}).
ΔP	:	Partial vapour pressure difference between greenhouse room and ambient moist air.
PV	:	Photovoltaic.
PV/T	:	Photovoltaic/thermal.
T_r	:	Greenhouse room air temperature (°C).
T_a	:	Ambient temperature (°C).
U_g	:	Overall heat transfer coefficient between greenhouse room air and ambient air through canopy cover (W m^{-2} $°C^{-1}$).
U_m	:	Overall heat transfer coefficient between greenhouse room air and ambient air through PV module (W m^{-2} $°C^{-1}$).
V	:	Volume of greenhouse (m^3).
V_L	:	Load voltage (V).
V_{oc}	:	Open circuit voltage (V).

Greek Symbols

Υ	:	Relative humidity of ambient air (decimal).
ρ_r	:	Density of greenhouse room air (kg m^{-3}).
$\eta_{i,canopy}$	:	Instantaneous thermal loss efficiency factor under natural mode through canopy cover.
$\eta_{i,natural}$	:	Instantaneous thermal loss efficiency factor under natural mode through vents.
$\eta_{i,forced}$	:	Instantaneous thermal loss efficiency factor under forced mode.
η_e	:	Electrical efficiency of PV module.
η_{eth}	:	Equivalent thermal efficiency of PV module.
η_{load}	:	Electrical load efficiency of PV module.

APPENDIX

The expressions/input data used in the paper were as follows:

- $$U_L \times \sum A_i = \left[U_g \times (\sum A_i - \sum A_m) + U_m \times \sum A_m\right]$$

  where, $U_L = 6.0\ W\ m^{-2}\ °C^{-1}$ (Tiwari, 2006)

- $$P(T) = \exp\left(25.317 - \frac{5144}{273.15 + T}\right)$$

- $$\Delta P = P(T_r) - \gamma \times P(T_a)$$

- $$\rho_r = \left[\frac{353.44}{273.15 + T_r}\right]$$

- N = 24.6 (calculated from average measured value of DC fan speed of 5 m sec^{-1})
- V = 9.26 m^3
- A_f = 6.5 m^2
- ΣA_i = 20.18 m^2
- ΣA_m = 1.21 m^2
- A_m = 0.60534 m^2
- A_v = 0.476 m^2

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