

Thermal Analysis of Photovoltaic Integrated Greenhouse Solar Dryer

Sumit Tiwari, Rohit Tripathi, G. N. Tiwari

Abstract—Present study focused on the utilization of solar energy by the help of photovoltaic greenhouse solar dryer under forced mode. A single slope photovoltaic greenhouse solar dryer has been proposed and thermal modelling has been developed. Various parameters have been calculated by thermal modelling such as greenhouse room temperature, cell temperature, crop temperature and air temperature at exit of greenhouse. Further cell efficiency, thermal efficiency, and overall thermal efficiency have been calculated for a typical day of May and November. It was found that system can generate equivalent thermal energy up to 7.65 kW and 6.66 kW per day for clear day of May and November respectively.

Keywords—Characteristics curve, Photovoltaic, Thermal modelling, Thermal efficiency.

I. INTRODUCTION

DRYING is one of the oldest food preservation techniques. Solar drying is the best among all drying processes as it is environmental friendly and economical. For food, demand is more than supply so the demand and supply gap for the food is rapidly growing due to population growth. The scarcity of food can be resolved either by increasing the supply of food or by controlling population growth or by both [1]. In developing countries, lack of suitable technology, lack of marketing channels, improper cultivation and fertilization, high post-harvest losses, improper transportation lead to a food loss from 10% to 40%. The process of drying (solar drying) is unquestionably cheapest method among all available drying processes because it does not require any expensive setup and energy source. For drying of plants, seeds, fruits, meat, fish, wood, and other agricultural or forest products as a means of preservation, open-air sun drying has been used since ancient time. Open sun drying has some limitations like, possible degradation due to biochemical or microbiological reactions, discoloration, insect infestation, lack of ability to control the drying process and so on. As we know that fruits like apricot, fig, grape, plum, and peach have been dried over centuries, but recently some other agricultural products like mango, apple, banana, pineapple, and pear have been also gaining importance [2]. Further to improve the quality of agricultural products, solar dryers came into existence. Solar dryers have been developed for two modes of operation namely natural mode and forced mode. Many researchers found that forced

mode drying is better than natural mode of drying in terms of controlling drying parameters [3], [4]. Smitabhindu et al. [5] derived a mathematical model for drying of bananas as a crop with the help of solar dryer under forced mode. In mathematical model, two differential equations are derived for collector and drying cabinet respectively. Further, program was developed on FORTRON and optimized collector area and the recycle factor was found to be 26 m² and 90%, respectively. Kumar and Tiwari [6] developed a thermal model of greenhouse dryer under forced mode for jaggery drying.

Integration with photovoltaic (PV) module of greenhouse dryer creates it free from grid connectivity for forced mode of operation. Barnwal and Tiwari [7] analyzed and compared the open sun drying with semi-transparent PV incorporated greenhouse drying. Semi-transparent PV modules were installed on the south inclined roof of the dryer to get maximum solar radiation. Solar greenhouse dryer coupled with PV-ventilation [8] used for drying of banana and peeled longan have been simulated and experimented. By experimentation, it was found that drying time is less in case of greenhouse drying comparative to open sun drying and further observed that greenhouse air temperature varies from 31 to 58^oC and 30 to 60^oC for peeled longan and banana respectively. Kumar and Tiwari [9] observed the effect of mass on heat transfer coefficient in open as well as greenhouse drying under forced mode on onion flakes. It was found that moisture evaporation rate in greenhouse was more than open sun drying during off sunshine hour.

II. EXPERIMENTAL SETUP

In the experimental setup, PV integrated greenhouse dryer has been taken. Experimental setup consists of three PV modules, DC fan (1 to 2), and a drying chamber. Photovoltaic module used in this drying system used for three purposes one is to give power to DC fan, second excess power to store or to use in other solar operated systems and third to avoid direct exposure of crop to avoid discoloration.

DC fans connected with photovoltaic panel are placed at north wall of PVT dryer. At the bottom of the PVT dryer has clearance of 0.1 m height for fresh air circulation. It has floor area of 1.025 m × 1.04 m and total volume is 0.71 m³. Upper and lower heights of the PVT dryer are 1.04 m and 0.4 m respectively. Inclination of roof facing due south is 30^o. The working principle of solar dryer is based on greenhouse effect in which short wave length solar rays can penetrate the glass envelope but after absorption sort wavelength converted into long wavelength. Due to low energy of long wavelength rays

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are unable to escape from the system and responsible for increasing the temperature of the system.

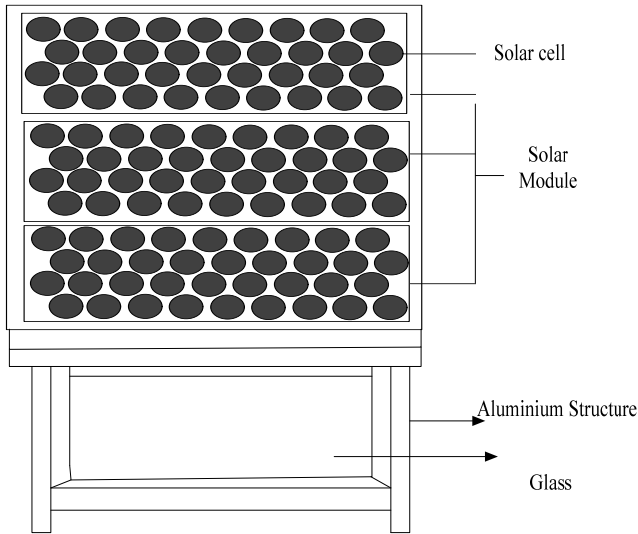


Fig. 1 (a) Front view of greenhouse dryer

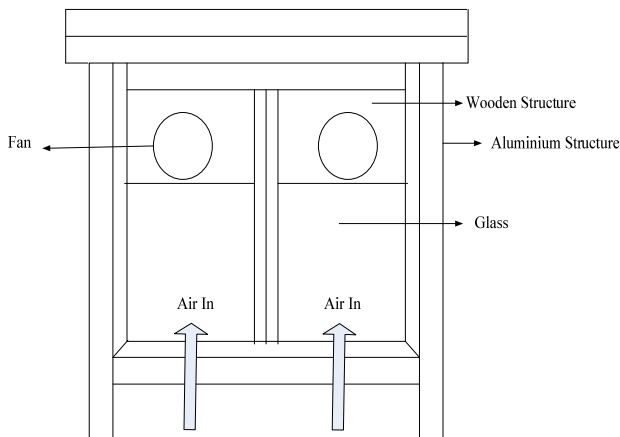


Fig. 1 (b) Back side view of greenhouse dryer

III. THERMAL MODELLING

The following assumptions have been taken for thermal modelling

- i. Heat capacity of metal used in greenhouse is neglected
- ii. Thin layer drying has been considered
- iii. Single tray has been used in modelling

a) Energy balance equation for PV

$$\alpha_c \tau_g \beta_c I(t) A_m = U_{ica} (T_c - T_a) A_m + U_{bcr} (T_c - T_r) A_m + \tau_g \beta_c \eta_c I(t) A_m \quad (1)$$

b) Energy Balance equation for crop

$$\alpha_{cr} \tau_g^3 (1 - \beta_c) I(t) A_m + \alpha_{cr} \tau_g A_c \sum I(i) + U_{bcr} (T_c - T_r) A_c = M_{cr} C_{cr} \frac{dT_{cr}}{dt} + h_{cr} (T_{cr} - T_r) A_c \quad (2)$$

c) Energy equation for green house chamber

$$\dot{M}_f C_f (T_r - T_a) = \dot{M}_f C_f (T_r - T_{fo}) + \sum (UA) (T_r - T_a) \quad (3)$$

In the steady state condition,

Thermal energy lost from the system = Thermal energy carried away by hot air

$$A_c h_{cr} (T_{cr} - T_r) = \dot{M}_f C_f (T_r - T_a) \quad (4)$$

$$T_r = \frac{A_c h_{cr} T_{cr} + \dot{M}_f C_f T_a}{A_c h_{cr} + \dot{M}_f C_f}$$

Putting the value of T_c and T_r from (1) and (4) in (2)

$$\frac{dT_{cr}}{dt} + \frac{1}{M_{cr} C_{cr}} \left(U_{ica} + \frac{U_{ira} A_i h_{cr} T_{cr} A_c}{A_c h_{cr} + \dot{M}_f C_f} \right) T_{cr} = \frac{1}{M_{cr} C_{cr}} \left((PF)(\alpha_c \tau_g \beta_c - \tau_g \beta_c \eta_c) A_c \right. \quad (5)$$

$$\left. + \alpha_{cr} \tau_g^3 (1 - \beta_c) A_m \right) I(t) + \alpha_{cr} \tau_g A_c \sum I(i) + \left(U_{ica} + \frac{U_{ira} A_i h_{cr} T_{cr} A_c}{A_c h_{cr} + \dot{M}_f C_f} \right) T_a$$

$$\frac{dT_{cr}}{dt} + a T_{cr} = f(t) \quad (6)$$

where, $a = \frac{1}{M_{cr} C_{cr}} \left(U_{ica} + \frac{U_{ira} A_i h_{cr} T_{cr} A_c}{A_c h_{cr} + \dot{M}_f C_f} \right) T_{cr}$ and

$$f(t) = \frac{1}{M_{cr} C_{cr}} \left((PF)(\alpha_c \tau_g \beta_c - \tau_g \beta_c \eta_c) A_c + \alpha_{cr} \tau_g^3 (1 - \beta_c) A_m \right) I(t) + \alpha_{cr} \tau_g A_c \sum I(i) + \left(U_{ica} + \frac{U_{ira} A_i h_{cr} T_{cr} A_c}{A_c h_{cr} + \dot{M}_f C_f} \right) T_a$$

From (6),

$$T_{cr} = \frac{f(t)}{a} (1 - e^{-at}) + T_{cro} e^{-at} \quad (7)$$

Crop temperature (T_{cr}) can be calculated by (7). T_r and T_c can be calculated by putting the value of T_{cr} in (4) and (1).

Cell efficiency can be written as [10]

$$\eta_c = \eta_o (1 - \beta_o (T_c - T_o)) \quad (8)$$

The module efficiency can be written as

$$\eta_m = \tau_g \beta_c \eta_c \quad (9)$$

Electrical energy from PV module can be written as

$$\dot{Q}_{u,el} = \eta_m A_m I(t) \quad (10)$$

Thermal energy gain from greenhouse dryer can be written as

$$\dot{Q}_{u,th} = \dot{M}_f C_f (T_{fo} - T_a) \quad (11)$$

$$\dot{Q}_{th,ov} = \dot{Q}_{u,th} + \frac{\dot{Q}_{el}}{0.38} \quad (12)$$

Thermal efficiency can be evaluated by the help of

$$\eta_{th} = \frac{\dot{M}_f C_f (T_{fo} - T_a)}{I(t)A} \quad (13)$$

Overall thermal efficiency can be calculated as

$$\eta_{ov,th} = \eta_{th} + (\eta_c / 0.38) \quad (14)$$

IV. RESULT AND DISCUSSION

The hourly variations of solar intensity and ambient temperature have been taken for May and November. Fig. 2 shows variation of total solar radiation, diffuse radiation, and ambient temperature. It is clear that for Delhi climatic conditions the solar radiation, diffuse radiation, and ambient temperature is more in May.

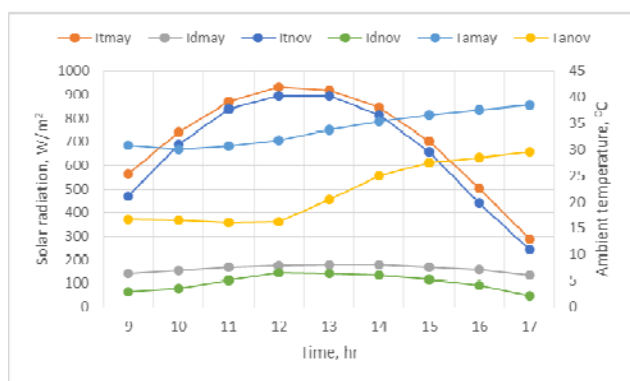


Fig. 2 Hourly Variation of total solar radiation, diffuse radiation and ambient temperature with respect to time for May and November

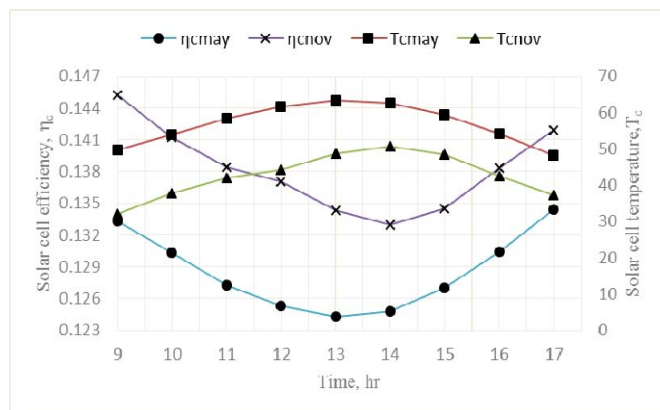


Fig. 3 Hourly Variation of solar cell temperature and solar cell efficiency with respect to time for May and November

Fig. 3 shows the variation of solar cell efficiency and solar cell temperature with respect to time. Figure shows that as the cell temperature increases the efficiency of cell decreases as expected from (8). Further, it is clear with graph that electrical efficiency is more in November.

Fig. 4 shows the hourly variation of ambient temperature, cell temperature, greenhouse chamber temperature, crop

temperature and outlet air temperature which is coming by help of MATLAB programming for May and November.

Fig. 5 shows hourly variation of overall thermal energy ($Q_{th,ov}$) with respect to time for a typical clear day of May and November. It was found that overall thermal energy increases up to 12 noon and further it decreases as the solar radiation decreases. Overall thermal energy for May and November found to be 7.65 kWh and 6.66 kWh per day respectively. Further, Fig. 6 shows the variation of electrical energy throughout a day. Overall thermal energy for May and November found to be 1.90 kWh and 1.91 kWh per day respectively. According to graph, the solar radiation is less in November but electrical energy is more due to higher solar cell efficiency.

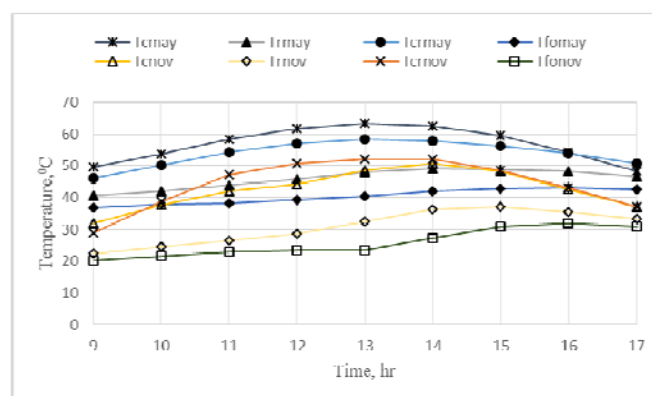


Fig. 4 Hourly variation of ambient temperature (T_a), cell temperature (T_c), greenhouse chamber temperature (T_r), crop temperature (T_{cr}) and outlet air temperature for a typical clear day of May and November

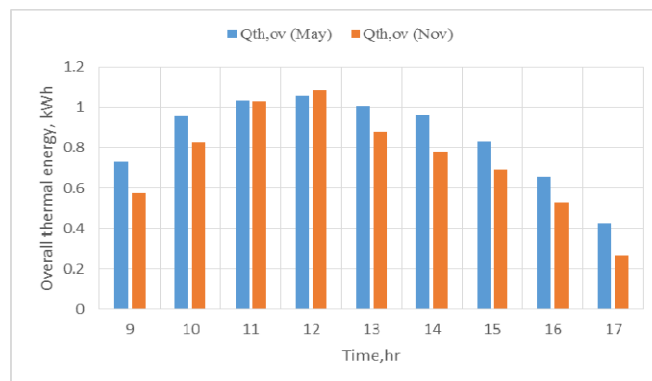


Fig. 5 Hourly variation of overall thermal energy ($Q_{th,ov}$) with respect to time for May and November

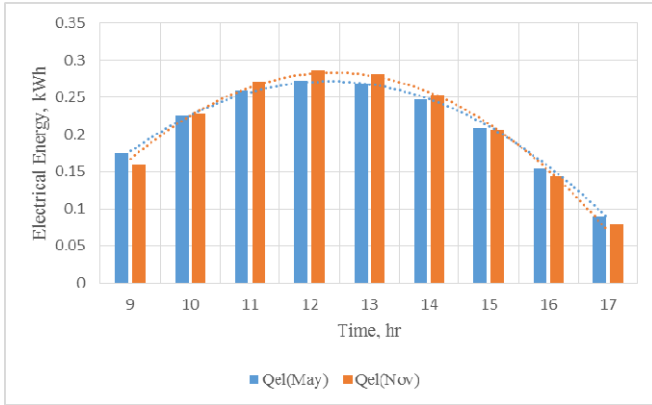


Fig. 6 Hourly variation of electrical energy ($Q_{el,ov}$) with respect to time for May and November

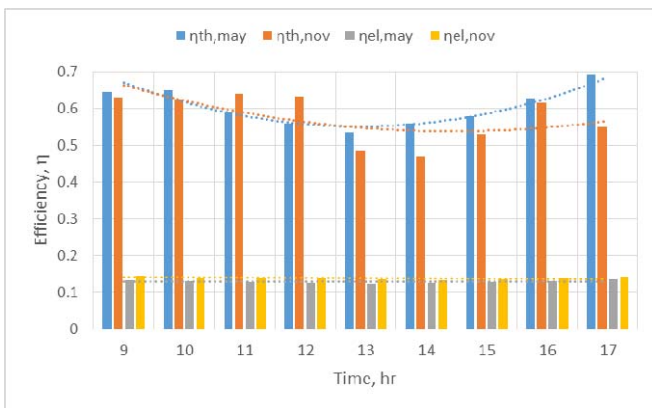


Fig. 7 Hourly variation of overall thermal efficiency (η_{th}) and electrical efficiency ($\eta_{el,th}$) with respect to time for May and November

Fig. 7 shows hourly variation of overall thermal and electrical efficiency. From the graph it is clear that overall thermal efficiency is more in the case of May and electrical energy is more in the case of November.

V. CONCLUSION

From the present study, following conclusion can be made as the cell temperature increases corresponding efficiency decreases. Total overall thermal energy for a clear day of May and November found to be 7.65 kWh and 6.66 kWh respectively. Electrical energy for a clear day of May and November found to be 1.91 kWh and 1.9 kWh respectively. Maximum overall thermal efficiency can be achieved 64 and 69 percent for November and May respectively. Analysis shows that there is very less output difference in summer and winter season so PV integrated greenhouse dryer can be used throughout the year. It is recommended that by increasing the roof area of greenhouse, more electricity can be produced which can be used for appliances in villages where grid connectivity is not available.

NOMENCLATURE

A_c Area of crop surface (m^2)

A_m Area of module (m^2)
 A_i Area of all side wall of dryer (m^2)
 C_f Specific heat of air (J/kg K)
 C_{cr} Specific heat of crop (J/kg K)
 d Diameter of fan (m)
 E_{in} Embodied energy (kWh)
 E_{aout} Total energy output per year (kWh)
 h_i Heat transfer coefficient (htc) inside solar drying chamber (W/m^2K)
 h_{cr} Total htc from crop surface to solar drying chamber (W/m^2K)
 h_{erc} Convective htc from crop surface to solar drying chamber (W/m^2K)
 h_{erev} Evaporative htc from crop surface to solar drying chamber (W/m^2K)
 h_o Heat transfer coefficient from top of module to ambient (W/m^2K)
 h_l Heat transfer coefficient from wall of dryer to ambient (W/m^2K)
 $I(t)$ Solar intensity (W/m^2)
 $I(i)$ Solar intensity on the wall of drying chamber (W/m^2)
 k_g Thermal conductivity of glass (W/mK)
 l_g Thickness of glass cover (m)
 \dot{M}_f Mass flow rate of air (kg/s)
 M_{cr} Mass of crop (kg)
 N Fan speed (RPM)
 P_{fan} Power of fan (W)
 P_{Tr} Partial pressure at green house chamber temperature (N/m^2)
 P_{Tcr} Partial pressure at crop temperature (N/m^2)
 T_a Ambient temperature ($^{\circ}C$)
 T_c Cell temperature ($^{\circ}C$)
 T_{cr} Crop temperature ($^{\circ}C$)
 T_r Drying chamber temperature ($^{\circ}C$)
 U_{ber} Heat transfer coefficient from bottom of module to drying chamber (W/m^2K)
 U_{ica} Heat transfer coefficient from top of module to ambient air (W/m^2K)
 α_c Absorptivity of solar cell
 α_{cr} Absorptivity of crop
 β_c Packing factor of module
 γ Relative humidity
 η_c Solar cell efficiency
 η_m Module efficiency
 v Wind velocity (m/s)
 v_l Air velocity in drying chamber (m/s)
 τ_g Transmissivity of glass

APPENDIX I

Formulae used to calculate different heat transfer coefficients used in thermal analysis are as:

$$v_1 = \frac{\pi^2 d^3 N}{4 \times 60 \times A_c} \quad \dot{M}_f = \rho A_c v_1$$

$$h_{cr} = h_{erc} + h_{erev} \quad h_{erc} = 2.8 + 3v_1$$

$$h_{erev} = \frac{0.01667 h_{cr} (P_{Tcr} - \gamma P_{Tr})}{T_{cr} - T_r} \quad h_o = 5.7 + 3.8v$$

$$U_{ica} = (A_c h_{cr} \dot{M}_f C_f) / (A_c h_{cr} + \dot{M}_f C_f)$$

$$h_i = 2.8 + 3v \quad h_l = 2.8 + 3v_1$$

$$U_{ber} = 2 \times ((l_g / k_g) + (1 / h_i))^{-1} \quad U_{ica} = ((l_g / k_g) + (1 / h_o))^{-1}$$

$$U_{wra} = (l_g / k_g) + (1 / h_i) \quad UA = A_m U_{tca} + A_i U_{wra}$$

$$P_{T_{cr}} = \exp(25.317 - (5144 / (273 + T_{cr})))$$

$$P_{T_r} = \exp(25.317 - (5144 / (273 + T_r)))$$

APPENDIX II

Various design parameters taken for calculation of different temperatures:

$\alpha_c = 0.9$	$\tau_g = 0.9$	$\beta_c = 0.6543$
$\eta_o = 0.15$	$\alpha_{cr} = 0.6$	$M_{cr} = 2 \text{ kg}$
$C_{cr} = 3900 \text{ J/kg K}$	$\gamma = 0.4$	$v = 1 \text{ m/s}$
$A_m = 1.3264 \text{ m}^2$	$A_i = 1.3264 \text{ m}^2$	$A_c = 1.2666 \text{ m}^2$
$C_f = 1005 \text{ J/kg K}$	$k_g = 0.816 \text{ w/mK}$	$d = 0.1 \text{ m}$
$N = 1100 \text{ rpm}$	$l_g = 0.003 \text{ m}$	$\rho = 1 \text{ kg/m}^3$

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