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Research Article

A Comparative Study for a Building Integrated Semitransparent Photovoltaic Thermal (BISPVT) System Integrated to Roof with and without Duct*

Kanchan Vats, R. K. Mishra, and Arvind Tiwari

Centre for Energy Studies, Indian Institute of Technology Delhi, Hauz Khas, New Delhi 110016, India
Address correspondence to Kanchan Vats, kanchanvats@gmail.com

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Abstract In this paper, a study has been carried out to evaluate annual energy and exergy of a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated to the roof of a building with and without duct. Comparisons of annual energy and exergy have been done by considering six different photovoltaic (PV) modules installed on the roof for cold climatic city of Srinagar, India. It is observed that the annual overall thermal energy is maximum for heterojunction with thin layer (HIT) and minimum for amorphous silicon (a-Si) for both with and without duct cases. It is also found that the annual overall exergy in HIT is 643 kWh and 610 kWh for both with and without duct cases, respectively.

Keywords building integrated photovoltaic thermal (BIPVT) system; PV module; exergy analysis

1 Introduction

A lot of experimental and theoretical studies have been done on building integrated photovoltaic thermal (BIPVT) system and it is found that integration of PV modules on the roof of a building produces a large amount of electrical energy as compared to integration of PV module on the facade. Thus BIPVT systems on roof save annual building electrical energy. Li et al. [3] found the annual building electricity saving of 1203 MWh by using semitransparent PV module. Sadineni et al. [7] saved 3.19 kWp of annual electrical energy by installing a system on the south facing roof of home in Las Vegas. System performance and system efficiency for a PV module installed on the roof and facade for a Samsung Institute of Engineering and Construction Technology (SIECT), Gihung, were evaluated by Yoo et al. [12]. They observed that the BIPV system on the building provides about 10% of the required electricity for a typical day. Song et al. [9] suggested that the PV modules installed at 30 °C performed better than vertical PV module in terms of annual power output. Agrawal and Tiwari [1] developed analytical expression for room air temperature for an opaque-type BIPVT system mounted on the rooftop of a building. They concluded that for a constant mass flow rate of air, room temperature is higher in series combination than any other type of combination of BIPVT system. In all researches, mono crystalline, poly crystalline silicon (m- or p-Si), and amorphous silicon (a-Si) modules have been considered. But in this paper alternative PV technologies like cadmium telluride (CdTe), copper indium gallium diselenide (CIGS), and a heterojunction comprised of a thin a-Si PV cell on top of a c-Si cell (HIT-hetrojunction with intrinsic thin layer) [2,5] have also been considered for the analysis. In this paper, a comparative study has been carried out to evaluate annual energy and exergy of a building integrated semitransparent photovoltaic thermal (BISPVT) system integrated to the roof of a building with and without duct, for different types of PV modules. Table 1 shows the module's efficiency $(\eta_{r,PV,m})$ under Standard Test Conditions (STC) and temperature coefficient $(\beta_{r,PV,m})$ for the selected PV modules.

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2 Problem identification

Eight different ways of integration of PV modules on a building have been discussed by Vats and Tiwari [10]. These semitransparent PV modules, those integrated on to the roof of a room without duct produce higher room temperature as compared to the with duct case. Therefore, a comparison between BISPVT systems integrated to roof, with and without duct (see Figures 1(a) and 1(b)) has been carried out by evaluating energy and exergy for different types of PV module materials.

Design specification and operating parameters considered for the study have been taken from Vats and Tiwari [10]. They have been used as input parameters for energy

Table 1: Values of module efficiency and temperature coefficient for different PV modules.

Type of PV module	Module efficiency STC (%) ($\eta_{r,PV,m}$)	Temperature coefficient % ($\beta_{r,PV,m}$)	References
m-Si	13.50	−0.40	Rüther et al. [6]
a-Si	6.30	−0.26	Yamawaki et al. [11]
p-Si	11.60	−0.40	Nann and Emery [4]
CdTe	6.90	−0.20	Nann and Emery [4]
CIS	8.20	−0.45	Nann and Emery [4]
HIT	17.00	−0.33	SANYO [8]

and exergy analysis. Climatic data for solar radiation, ambient temperature, and number of clear days for Srinagar have been obtained from Indian Metrological Department (IMD), Pune.

3 Thermal modeling for building integrated semitransparent photovoltaic thermal (BISPVT) system integrated to the roof

The following assumptions have been made to write the energy balance equation of a BISPVT system integrated to the roof with duct:

(1) One dimensional heat conduction in quasi-steady state is considered.
(2) There is no temperature stratification in the air of a room and semitransparent PV module.
(3) The room is thermally insulated and physical properties of air are constant over operating temperatures.

3.1 Energy balance equation for semitransparent PV module and room air temperature

Using the expression as given by Vats and Tiwari [10], the energy balance equation of room air temperature for BISPVT system with and without air duct is

$$T_r = \frac{f(t)}{a}\big(1-\exp(-at)\big) + T_{ri}\exp(-at). \tag{1}$$

The expression for "a" and "$f(t)$" is different for with and without air duct.

3.2 Electrical and thermal energy of BISPVT system integrated to the roof

3.2.1 Electrical energy

The hourly electrical efficiency of the PV module is given by the formula

$$\eta_{PV,m,hourly} = \eta_{ref,PV,m}\left[1-\beta_{ref,PV,m}\left(T_{c,hourly}-25\right)\right]. \tag{2}$$

The expression for hourly electrical power (W) is

$$E_{el,hourly} = \eta_{PV,m,hourly} \times A_{PVroof} \times I(t)_{hourly}. \tag{3}$$

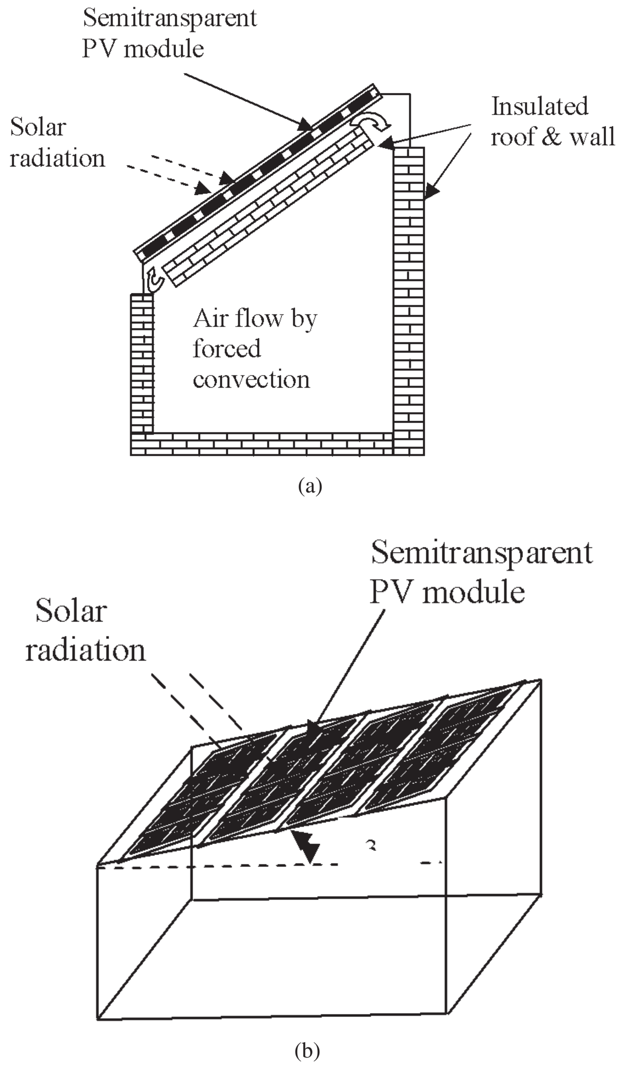

Figure 1: View of a building integrated semitransparent photovoltaic thermal system integrated to roof (a) with duct and (b) without duct.

The expression for annual electrical energy (kWh) for BISPVT system integrated to the roof with and without air duct is

$$E_{el,annual} = \sum_{k=1}^{12} E_{el,monthly,k}. \tag{3a}$$

3.2.2 Thermal energy

Rate of useful thermal energy (W) obtained from BISPVT system with duct is

$$q_{u,hourly} = \dot{m}_a c_a\left[T_{fo} - T_r\right]. \tag{4}$$

However, rate of useful thermal energy for BISPVT system integrated to roof without air duct is

$$q_{u,hourly} = A_{PVroof}\left[U_{Tc,r}\left(T_{c,hourly} - T_{r,hourly}\right)\right]. \tag{4a}$$

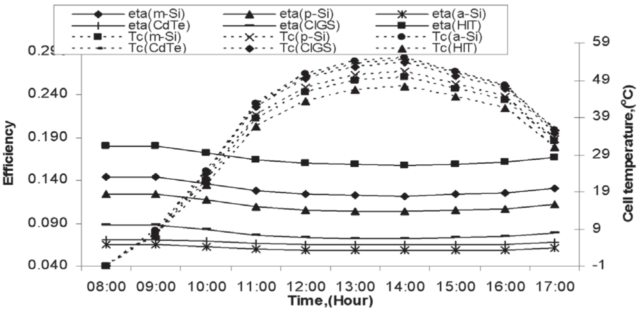

Figure 2: Hourly variation of efficiency and cell temperature for BISPVT system integrated to roof with duct, for six different PV modules.

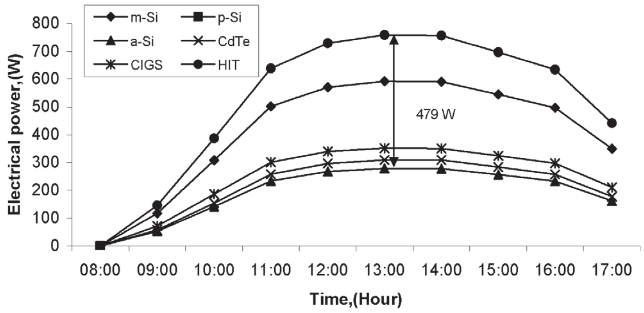

Figure 3: Hourly variation of electrical power for BISPVT system integrated to roof with duct for six different PV modules.

Further, annual thermal energy (kWh) is given as

$$Q_{th,annual} = \sum_{k=1}^{12} \frac{q_{th,monthly,k}}{1000}. \tag{4b}$$

3.3 Overall thermal energy of BISPVT system

The conventional electrical output can be converted to an equivalent thermal output by using the following expression:

$$E_{th,monthly} = \frac{E_{el,monthly}}{0.38}. \tag{5}$$

Similarly, annual equivalent thermal energy is obtained by summing the monthly equivalent thermal energy and can be written as

$$E_{th,annual} = \sum_{k=1}^{12} E_{th,monthly,k}. \tag{6}$$

The overall annual thermal energy is the sum of annual thermal energy $(Q_{th,annual})$ and annual equivalent thermal energy $(E_{th,annual})$:

$$(Q_{ov})_{th,annual} = Q_{th,annual} + E_{th,annual}. \tag{7}$$

3.4 Overall exergy analysis of BISPVT system

The expression for monthly exergy for BISPVT system integrated to roof with air duct is written as

$$Ex_{th,monthly} = Q_{th,monthly}\left[1 - \frac{\overline{T_a}+273}{\overline{T_{fo}}+273}\right]. \tag{8}$$

However, the expression for monthly exergy for BISPVT system integrated to roof without air duct will be

$$Ex_{th,monthly} = Q_{th,monthly}\left[1 - \frac{\overline{T_a}+273}{T_r+273}\right]. \tag{8a}$$

Similarly, the expression for annual exergy is written as

$$Ex_{th,annual} = \sum_{k=1}^{12} Ex_{th,monthly,k}. \tag{9}$$

Annual overall exergy is the sum of annual exergy $(Ex_{th,annual})$ and annual electrical energy $(E_{el,annual})$

$$Ex_{annual} = Ex_{th,annual} + E_{el,annual}. \tag{10}$$

4 Results and discussion

Hourly variations of cell efficiency and cell temperature for six different PV modules are shown in Figure 2. In all the cases, it is observed that the increase in cell temperature decreases the cell efficiency. In case of HIT, the cell temperature is found to be 38 °C for maximum efficiency of 16% (at 1400 h) and in case of a-Si, the maximum cell temperature is 44 °C for minimum efficiency of 6% (at 1400 h). Hence, variation in cell efficiency is 6% to 16% for rise in cell temperature of 6 °C. The hourly variation of electrical power for BISPVT system integrated to roof with duct for all types of PV module is shown in Figure 3. It is observed from the figure that the electrical power is maximum for HIT and minimum for a-Si. It is 479 W higher in HIT because of its maximum electrical efficiency. Therefore, HIT becomes the best alternative for the production of electrical power.

Figure 4 shows hourly variations of thermal energy and room temperature. From the figure, the observed maximum and minimum thermal energy for a-Si and HIT is 725 W and 650 W, respectively. Higher cell temperature in a-Si produces higher thermal energy resulting in higher room temperature. However, the change in room temperature for all six PV modules is found to be marginal. Hence, for space heating purpose, a-Si is the best alternative at the cost of lower electrical energy.

A comparison between the annual overall thermal energy for six PV modules for BISPVT system integrated to roof, with and without duct case, is shown in Figure 5. It is found that the annual overall thermal energy is approximately 15% higher for those with duct than for those without duct case. This is due to higher rate of heat transfer from the PV cell to flowing air in duct, with forced circulation of air. Therefore, the overall annual thermal

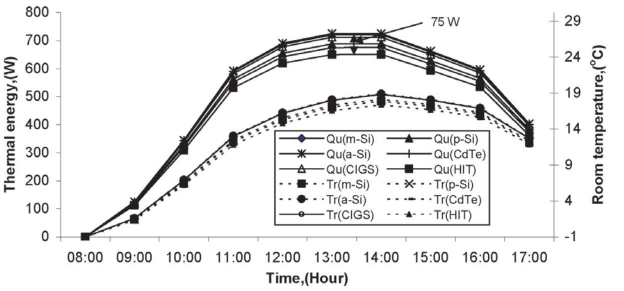

Figure 4: Hourly variation of thermal energy and room air temperature for BISPVT system with duct for different PV modules.

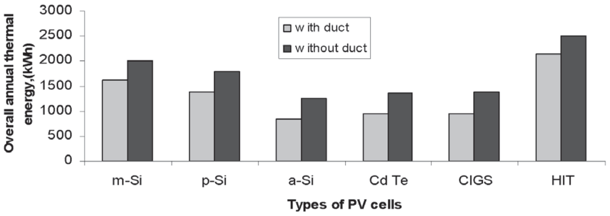

Figure 5: Annual overall thermal energy for (a) with duct and (b) without duct for different types of PV module.

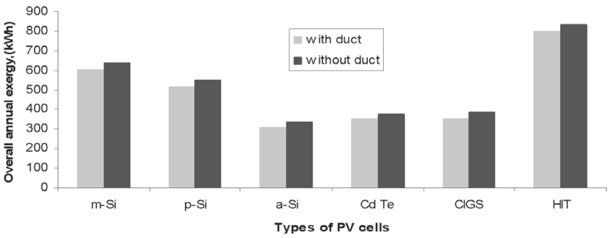

Figure 6: Annual overall exergy for (a) with duct and (b) without duct for different types of PV module.

energy is high in those with duct case. In case of without duct, the heat transfer rate is low because of the decrease in temperature difference with time across the PV cell and air on account of natural flow. However, in with duct case, the overall temperature rise of room air in a day is low due to the heat accumulation in material of ducting (i.e., roof). Thus, the provision of forced flow of air with duct is economical and cost effective only in case of retrofitting in existing buildings. It is also observed that the annual overall thermal energy is maximum for HIT and minimum for a-Si for both with and without duct cases. The observed values from the figure for HIT (with duct) are 2103 and (without duct) 1820 kWh. However, for a-Si the observed values are 1155 (with duct) and 887 kWh (without duct). Figure 6 shows the comparison of annual overall exergy for both with and without duct cases. The figure shows that the maximum values of overall annual exergy for HIT is 643 kWh and 610 kWh for with duct and without duct, respectively.

5 Conclusions

(1) HIT is the best alternative for production of electrical power.

(2) Higher cell temperature in a-Si produces higher thermal energy.

(3) Overall annual thermal energy is approximately 15% higher in with duct than without duct case.

(4) BISPVT system integrated to roof with duct is economical and cost effective only in case of retrofitting in existing buildings.

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