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Exergetic analysis of building integrated semitransparent photovoltaic module in clear sky condition at Bhopal India

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ABSTRACT

In this research paper the energy, exergy and power generation of building integrated semitransparent photovoltaic (BISPV) modules for roof and facade has been evaluated. Solar radiation intensity on BISPV modules surfaces is an essential parameter for assessing energy and exergy. The experimental setup consists of two BISPV modules, each of 75W rating, which has been conducted on a clear sky day at roof and façade of Energy Centre building, MANIT Bhopal, India. It is observed that the energy efficiency varies between 11-18% at roof and 13-18% at facade throughout the day. The maximum value of electrical efficiency of BISPV module is 85% at roof and 72% at façade.
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1. Introduction

Energy is considered as a prime agent in the generation of wealth and a significant factor in the economic development. Building integrated photovoltaic system, where photovoltaic cells are integrated within the climate envelopes of building and utilizing solar radiation to produce energy in the form of electricity. Building integrated photovoltaic systems replace part of conventional building materials and systems in the climate envelope of buildings, such as the roof and facades. To improve the performance of building, passive strategies such as energy efficient facade can be used. Improve façade and roof elements energy performance is the key as they are interface between the indoor and outdoor environments. Building integrated semitransparent photovoltaic (BISPV) started to become important in late 1990s. It has been considered as an attractive technology for building integration. Building integrated semitransparent photovoltaic is a new type of building material, which provides green energy as well as building preservation. Apart from generating electricity, BISPV modules can be customized in different dimension, thickness, shape and color. Semitransparent solar modules, BIPV applications demand flexibility in the PV module having both an aesthetic and functional role. BIPV systems can be installed as stand alone or grid connected systems. The types of systems utilized can consist of sloping roof systems, flat roof systems, façade systems wherein the modules replace large glass surface and integrated systems as façade accessories in which the modules are arranged as shading or solar protection systems. First generation (mono or poly crystalline) cells are usually integrated with roof covering, together with standard roof tiles. They have also been utilized as facades, replacing traditional glass as windows.

Agrawal and Tiwari [1] developed analytical expression for room air temperature for an opaque type BIPVT system mounted on the rooftop of a building. Fung and Yang [2] developed the semitransparent photovoltaic module heat gain

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model and experimentally verified the thermal performance of semitransparent BIPV modules. Ordenes et al. [3] installed a PV system on rooftop of a building and concluded that it yields more energy than any of the vertical facade. They observed that more than 45% of energy will be produced on the rooftop portion of PV installation. Oh et al. [4] developed a cost-effective method for integration of existing grid with new and renewable energy sources on public buildings in Korea. Proper combination of new and renewable energy sources is suggested by detailed numerical calculation based on the hourly energy demand pattern data obtained from field studies for the buildings. Wu et al. [5] evaluate performance of heat pipe photovoltaic/thermal (PV/T) hybrid system and found the overall thermal, electrical and exergy efficiencies of the heat pipe PV/T hybrid system corresponding to 63.65%, 8.45% and 10.26%, respectively can be achieved under the operating conditions. The varying range of operating temperature for solar cell on the absorber plate is less than 2.5 °C. The heat pipe PV/T hybrid system is viable and exhibits the potential and competitiveness over the other conventional BIPV/T systems. Koyunbaba et al. [6] developed the simulation model with experimental results of a model BIPV Trombe wall built in Izmir, Turkey and they found that 10% of solar radiation transmittance has been supplied by using a Semi-transparent a-Si solar cell. Thus, thermal energy input to the system increases compared to other BIPV systems. Meanwhile, the experimental daily average electrical and thermal efficiency of this system can reach 4.52% and 27.2% respectively. Chandrasekhar et al. [7] concluded Flat solar photovoltaic (PV) modules are widely being used in domestic and industrial buildings for meeting the electric power demands. Higher operating temperatures of these PV modules result in lower electrical power yield and conversion efficiency. Shan et al. [8] reviewed the photovoltaic–thermal (PVT) solar collector system using various working fluid via dynamic simulation. The performance of a hybrid PVT collector using refrigerant as working fluid was evaluated and analysed for the typical weather condition in Nanjing, China. The simulation results showed the influence of the meteorological parameters and the evaporating temperature on the photovoltaic and thermal performance of the hybrid photovoltaic–thermal collector. Shan et al. [9] carried out Dynamic performances modeling of a photovoltaic–thermal collector with water heating in buildings. The results indicated that the less series-connected PV modules, the lower inlet temperature of water and the higher mass flow rate of water resulted in the high photovoltaic efficiency. Vats et al. [10] studied the effect of packing factor of semitransparent photovoltaic (PV) module integrated to the roof of a building, on the module and room air temperature, and electrical efficiency of PV module. It has been observed that the decrease in the temperature of PV module due to decrease in packing factor, increases its electrical efficiency. It is also found that the decrease in packing factor increases the room temperature. Maximum annual electrical and thermal energy is found to be 813 kWh in HIT and 79 kWh in a-Si PV module respectively with packing factor of 0.62. Dubey et al. [11] analysed energy and exergy of PV/T air collectors connected in series. It is found that the collectors fully covered by PV module and air flows below the absorber plate gives better results in terms of thermal energy, electrical energy and exergy gain. Physical implementation of BIPV system has also been evaluated. If this type of system is installed on roof of building or integrated with building envelope will simultaneously fulfil the electricity generation for lighting purpose and hot air can be used for space heating or drying. Kılkıs [12] studied energy consumption and CO_2 emission responsibilities of terminal buildings. As a result, this study has exemplified the essential boundaries for energy consumption analysis envelope for an airport terminal building and its true emissions responsibility. Sarhaddi et al. [13] studied the exergetic performance of a solar photovoltaic thermal (PV/T) air collector. It is observed that the modified exergy efficiency obtained in this paper is in good agreement with the one given by the previous literature. It is also found that the thermal efficiency, electrical efficiency, overall energy efficiency and exergy efficiency of PV/T air collector is about 17.18%, 10.01%, 45% and 10.75% respectively for a sample climatic, operating and design parameters. Agrawal and Tiwari [14] Performed an analysis of the building integrated photovoltaic thermal (BIPVT) system fitted as rooftop of a building to generate electrical energy and also to produce thermal energy for space heating. The results indicate that although the mono-crystalline BIPVT system is more suitable for residential consumers from the viewpoint of the energy and exergy efficiencies, the amorphous silicon BIPVT system is found to be more economical. Buker et al. [15] analysed performance evaluation and techno-economic of a novel building integrated PV/T roof collector. The experimental values indicate that water temperature difference could reach up to 16 °C, and the system would achieve up to 20.25% overall thermal efficiency. The energy and exergy analysis is performed to observe the increase in energy and exergy efficiencies due to the implementation of concealed heat extraction component. Vats, Tiwari [16] evaluated the Performance of a building integrated semitransparent photovoltaic thermal system for roof and façade. It is observed that there are maximum (18 °C) and minimum (2.3 °C) rise in room air temperature for semi-transparent photovoltaic thermal (SPVT) roof without air duct and opaque photovoltaic thermal (OPVT) facade with air duct respectively. The electrical and exergy results presented in this study are in good agreement with the experimental results of Sudhakar and Srivastava [27]. Shukla et al. [28] evaluated exergy efficiency of amorphous and polycrystalline PV module throughout the day. The energy efficiencies of both the modules are found to be always higher than that of exergy efficiencies and power conversion efficiencies.

A number of research studies have been conducted on the energy and exergy evaluation of BIPV systems. This research paper aims at determining the performance of building integrated semitransparent photovoltaic (BISPV) modules for roof and facade Solar radiation intensity on BISPV modules surfaces is an essential parameter for assessing energy performance of the BISPV modules. Performance analysis through energy and exergy efficiencies and evaluation of electrical and thermal energy output of BISPV system for roof and façade of building has been presented in this paper.

2. Problem identification

2.1. Energy efficiency

The actual output of the BISPV module may be defined as

$$P_m = V_{oc} \times I_{sc} \times FF \tag{1}$$

where V_{oc} is open circuit voltage, I_{sc} is short circuit current and FF is fill factor is defined as below:

$$FF = \frac{V_m I_m}{V_{oc} I_{sc}} \tag{2}$$

and

$$P_m = V_m I_m \tag{3}$$

The energy efficiency can be defined as below [17,18]:

$$\eta = \frac{V_m I_m}{I_s A_{mod}} \tag{4}$$

where I_s solar radiation intensity and A_{mod} area of BISPV module.

2.2. Electrical efficiency

The temperature dependence of BISPV module electrical efficiency is given as [19]

$$\eta_{elect} = \eta_{ref}\left[1 - \beta_{ref}(T_{mod} - T_{ref}) + \gamma \log_{10} I_s\right] \tag{5}$$

where β_{ref} is temperature coefficient and γ is solar radiation coefficient having values of about 0.12 for crystalline silicon modules.

The traditional linear expression for BISPV electrical efficiency is given as [20,21]

$$\eta_{elect} = \eta_{ref}\left[1 - \beta_{ref}(T_{mod} - T_{ref})\right] \tag{6}$$

and

$$\beta_{ref} = \frac{1}{T_0 - T_{ref}} \tag{7}$$

where T_0 is the high temperature at which the PV modules electrical efficiency drop to zero. The solar radiation dependence of BISPV module electrical efficiency is given as [22]

$$\eta_{elect} = \eta_{ref}\left[1 - \beta_{ref}\left\{T_{amb} - T_{ref} + (T_{STC} - T_{amb})\frac{I_s}{I_{STC}}\right\}\right] \tag{8}$$

and

$$\eta_{elect} = \eta_{ref}\left[1 - \beta_{ref}\left\{T_{amb} - T_{ref} + \frac{9.5}{5.7 + 3.8V_w}(T_{STC} - T_{amb})\frac{I_s}{I_{STC}}\right\}\right] \tag{9}$$

2.3. Exergy efficiency

The exergy efficiency of a system is given as

$$\Psi = \frac{\dot{E}_x}{\dot{E}_{x_{solar}}} \tag{10}$$

where $\dot{E}_x$ is the exergy of the BISPV system is mainly electrical power output of the system [23,28] and

$$\dot{E}_x = V_m I_m - \left[1 - \left(\frac{T_{amb}}{T_{mod}}\right)\right]\dot{Q} \tag{11}$$

where $\dot{Q}$ is the convective and radiative heat transfer coefficient from photovoltaic cell to ambient.

and

$$\dot{Q}=h_{ca}A_{mod}(T_{mod}-T_{amb}) \tag{12}$$

where

$$h_{ca} = 5.7 + 3.8V_w \tag{13}$$

V_w = wind velocity

Then $\dot{E}_x = V_m I_m - \left[1-\left(\frac{T_{amb}}{T_{mod}}\right)\right]\left[h_{ca}A_{mod}(T_{mod}-T_{amb})\right]$

and $\dot{E}_{x_{solar}}$ is the exergy rate from the solar irradiance in W/m^2 is given as [23,24]

$$\dot{E}_{x_{solar}} = \left[1-\left(\frac{T_{amb}}{T_{mod}}\right)\right]I_s A_{mod} \tag{14}$$

Then exergy efficiency of the BISPV system can be given as [28]

$$\Psi_{PV}=\frac{V_m I_m - \left[1-\left(\frac{T_{amb}}{T_{mod}}\right)\right](5.7+3.8v)}{\left[1-\left(\frac{T_{amb}}{T_{mod}}\right)\right](I_s A_{mod})} \tag{15}$$

The exergy rate of solar irradiance can also be calculated by using Petela's formula [24,25]

$$\Psi_{PV}=\frac{V_m I_m - \left[1-\left(\frac{T_{amb}}{T_{mod}}\right)\right]\left[h_{ca}A_{mod}(T_{mod}-T_{amb})\right]}{\left[1+\left(\frac{1}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)^4-\left(\frac{4}{3}\right)\left(\frac{T_{amb}}{T_{sun}}\right)\right](I_s A_{mod})} \tag{16}$$

2.4. Electrical and thermal energy of BISPV system for roof and façade

2.4.1. Electrical energy [26]

The hourly electrical efficiency of the BISPV module is given by

$$\eta_{BISPV,hourly} = \eta_{ref}\left[1-\beta_{ref}\left(T_{mod,hourly}-25\right)\right] \tag{17}$$

where β_{ref} and η_{ref} are module efficiency and temperature coefficient for thin film BIPV module and their value given in Tables 1 and 2.

Table 1
Specification of 75 W BISPV module.

(At STC, 1000 W/m^2, AM 1.5 and 25 °C cell temperature)	
Parameters	**Value**
Maximum Power, P_m	75 W
Voltage at max. power, V_m	17.0 V
Current at max. power, I_m	4.45 A
Short Circuit Current, I_{sc}	4.79 A
Open Circuit Voltage, V_{oc}	21.8 V
Efficiency of module	17.23%
Area of the module	0.4353 m^2

Table 2
Electrical and meteorological parameters measured in the experimentation.

Parameters	Symbol	Unit
Maximum Current	I_m	A
Maximum Voltage	V_m	V
Maximum Power	P_m	W
Ambient Temperature	T_{am}	^{0}C
Wind Speed	v_w	m/sec
Solar Intensity	G	W/m^2
Short Circuit Current	I_{sc}	A
Module Temperature	T_{cell}	°C
Open Circuit Voltage	V_{oc}	V

The hourly electrical power (W) is for roof of the BIPV system

$$E_{electrical,hourly} = \eta_{BISPV,hourly} \times A_{mod,roof} \times I_{s,hourly} \quad (18)$$

Similarly For facade of the BIPV system

$$E_{electrical,hourly} = \eta_{BISPV,hourly} \times A_{mod,facade} \times I_{s,hourly} \quad (19)$$

The daily electrical energy in kWh for roof and facade is given by

$$E_{electrical,daily} = \sum_{i=1}^{N} \frac{E_{electrical,hourly,i}}{1000} \quad (20)$$

where N is number of sunshine hours per day.

The monthly electrical energy in kWh for roof and facade is given by

$$E_{electrical,monthly} = E_{electrical,daily} \times n_0 \quad (21)$$

where n_0 is number of clear days in a month.

The annual electrical energy in kWh for roof and facade is given by

$$E_{elect,annual} = \sum_{k=1}^{12} E_{electrical,monthly,k} \quad (22)$$

2.4.2. Thermal energy [26]

Rate of useful thermal energy (W) obtained from BIPV system for roof and facade is

$$Q_{thermal,hourly} = A_{mod}\left[U_{Tc}\left(T_{mod,hourly} - T_{amb,hourly}\right)\right] \quad (23)$$

The daily thermal energy in kWh for roof and façade is given by

$$Q_{thermal,daily} = \sum_{i=1}^{N} \frac{Q_{thermal,hourly,i}}{1000} \quad (24)$$

Similarly, monthly and annual thermal energy (kWh) for roof and façade is given by

$$Q_{thermal,monthly} = \sum_{j=1}^{N} \frac{Q_{thermal,daily,j}}{1000} \quad (25)$$

and

$$Q_{thermal,annual} = \sum_{k=1}^{12} \frac{Q_{thermal,monthly,k}}{1000} \quad (26)$$

2.5. Overall thermal energy of BISPV system [26]

The monthly equivalent thermal energy is given by

$$E_{thermal,monthly} = \frac{E_{electrical,monthly}}{0.38} \quad (27)$$

Similarly, annual thermal energy is given as

$$E_{thermal,annual} = \sum_{k=1}^{12} E_{thermal,monthly,k} \quad (28)$$

Therefore the overall annual thermal energy is given as

$$Q_{ov,thermal,annual} = Q_{thermal,annual} + E_{thermal,annual} \quad (29)$$

2.6. Overall exergy analysis of BISPV system

The monthly equivalent exergy is given as

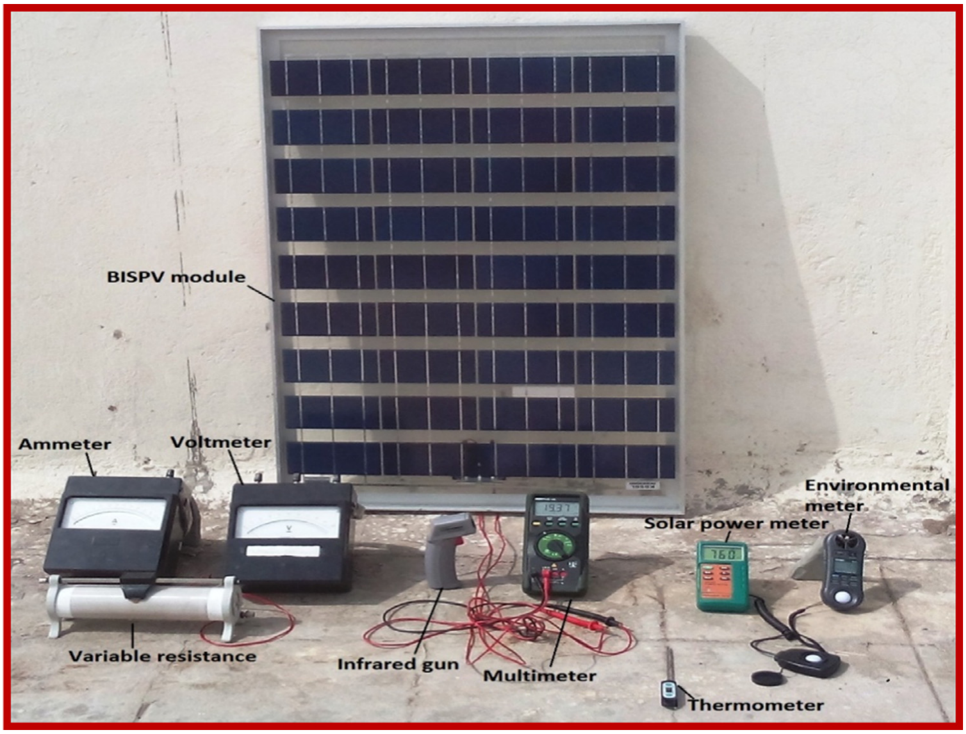

Fig. 1. Experimental set-up at facade of Energy Centre, MANIT Bhopal, India.

$$E_{Xth,monthly} = Q_{thermal,monthly}\left[1 - \frac{T_{amb}+273}{T_{mod}+273}\right] \quad (30)$$

Similarly the annual exergy is given as

$$E_{Xth,annual} = \sum_{k=1}^{12} E_{Xth,monthly,k} \quad (31)$$

Therefore the overall exergy is given as

$$E_{Xannual} = E_{Xth,annual} + E_{elect,annual} \quad (32)$$

3. Experimentation

Two building integrated semitransparent photovoltaic (BISPV) modules each of 75 W rating were selected to conduct performance analysis at roof and façade of the building. The specification of both BISPV module at standard test condition as given by manufacturer are listed in Table 1. Experiment was conducted on a clear sky day at roof and façade of Energy Centre building, Maulana Azad National Institute of Technology, Bhopal, India (22nd March 2015) from 9 a.m. to 5 p.m. Experimental setup is shown in Fig. 1 and 2. Electrical and metrological parameters measured for every one hour of both BISPV module are listed in Table 2. The various instruments used for measuring parameters in terms of range, resolution and sampling time for both BISPV module at roof and façade of building are listed in Table 3.

The following assumptions have been made before performing experiment on BISPV module:

- Fill factor is assumed to be constant because fill factor varies according to ambient temperature and solar radiation intensity.
- Overall heat loss coefficient from BISPV module both convection and radiation losses is considered.
- Design, operating and climatic parameters are considered at standard test condition (STC).
- For the assessment of electrical and exergy efficiency of the BISPV system it has been assumed that exergy content received by photovoltaic surface is fully utilized to generate maximum electrical energy.

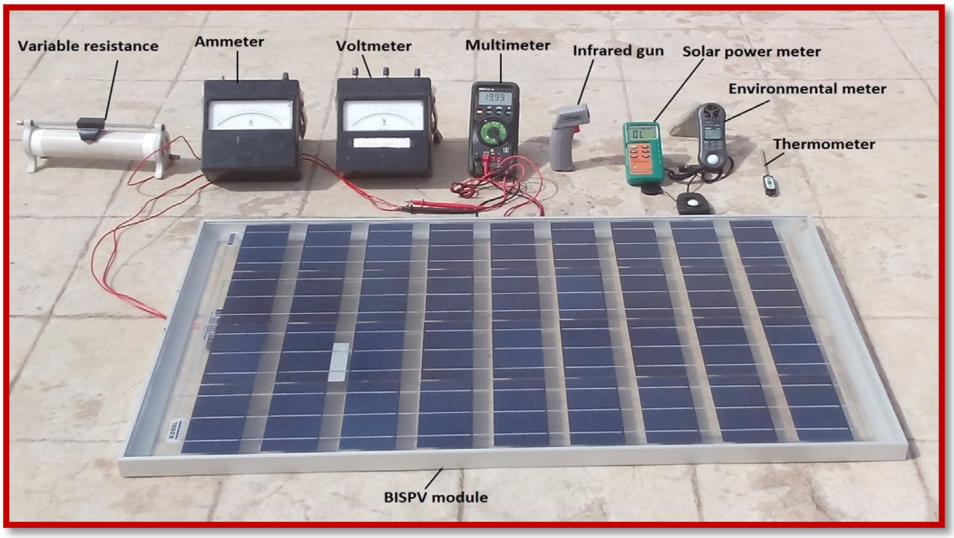

Fig. 2. Experimental set-up at roof floor of Energy Centre, MANIT, Bhopal, India.

Table 3
Specifications of measuring instruments used in experimentation.

Measuring instruments	Rating and range	Resolution	Application
Multimeter	R(0–100Ω),V(0–1000 V),	10 μV to10 mV 10 nA to 10 μA	PV module output Current, Voltage and resistance
(Rish muth 155)	I(0–300 mA,0–10 A)	100 mΩ to 100 Ω and resistance	
Digital thermometer	−50 °C to 300 °C	0.1° for −19.9°	Ambient temperature
Anemometer	0.4–30 m/s	0.1 m/s	Wind speed
Solar power meter TM 207	200 W/m^2, 634BTU/(ft2xh)	Sampling time 0.25 s	Solar radiation intensity
Infrared thermometer (Infrared gun) Ray Tek	−18 °C to 275 °C (0–525 °F)	0.2 °C	PV module temperature

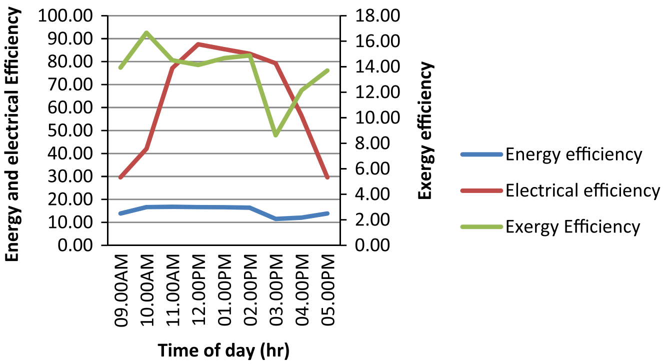

Fig. 3. Variation of energy, electrical and exergy efficiency of BISPV module for roof.

4. Results and discussion

Actual experimental data obtained for a typical clear sky day at Energy Centre, Bhopal were applied to investigate the effect of the ambient conditions on the performance of BISPV module. The exergy efficiency of the BISPV module has been calculated on the basis of the second law of thermodynamics, by taking exergy of solar radiation. An energy and exergy balance for the BISPV module was carried out.

Fig. 3 and 4 shows the variation of exergy, energy and electrical efficiency of the BISPV module at roof and façade of the building. The energy efficiency is varies between 11% and 18% at roof and 13% and 18% at facade throughout the day. The maximum value of electrical efficiency was 85% at roof and 72% at façade of the BISPV module. The variation of exergy

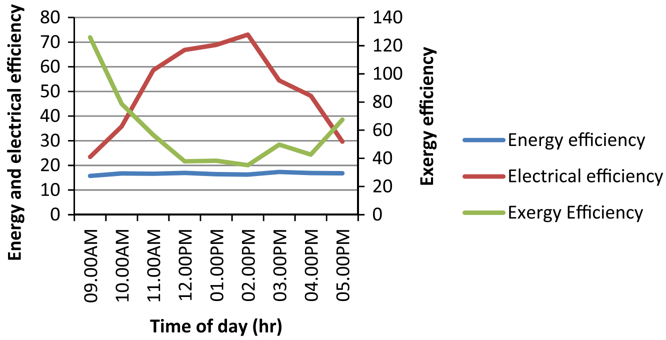

Fig. 4. Variation of energy, electrical and exergy efficiency of BISPV module for façade.

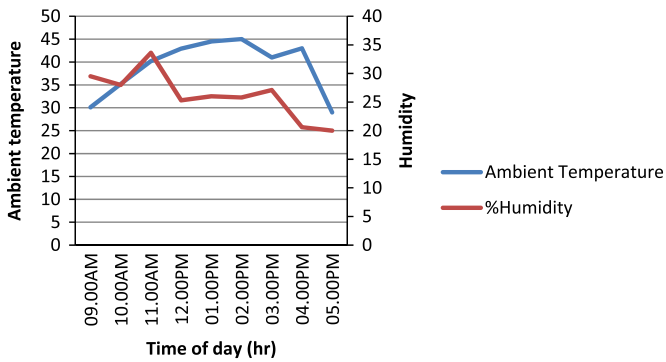

Fig. 5. Variation of Ambient temperature and humidity for roof.

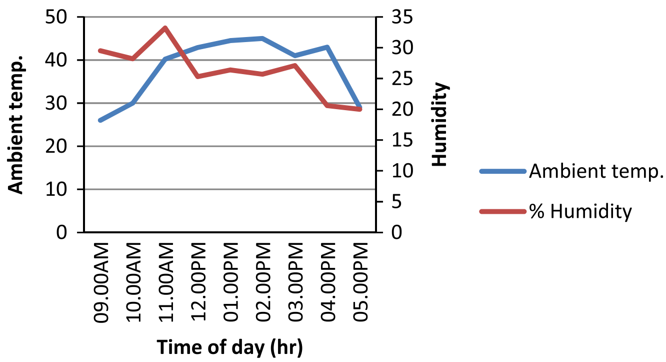

Fig. 6. Variation of Ambient temperature and humidity for façade.

efficiency of BISPV module at roof and façade of the building is shown in Fig. 3 and 4. The exergy efficiency of the BISPV module increases with increase in solar intensity. The low exergy due to the irreversibility of the photovoltaic conversion process.

Fig. 5 and 6 shows the variation of ambient temperature and humidity for experimentation at roof and façade of the building. The ambient temperature varied from 28–36 °C and humidity varied from 19–42% on a clear sky condition at Bhopal.

Figs. 7 and 8 shows the variation of solar radiation intensity and module temperature of BISPV system for roof and façade of the building. Solar radiations is in the range of 250–1000 W/m^2 at roof and 210–610 W/m^2 at façade. BISPV module temperature varies from 28–58 °C at roof and 28–52 °C at façade of the building.

It has been found from Table 4, the energy and exergy of BISPV module at façade has been better when compared to BISPV module at rooftop of building. The results are true in terms of electrical energy, thermal energy and thermal exergy.

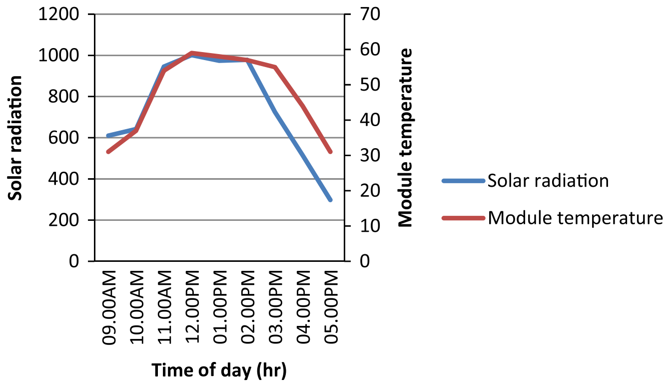

Fig. 7. Variation of solar radiation and module temperature of BISPV module for roof.

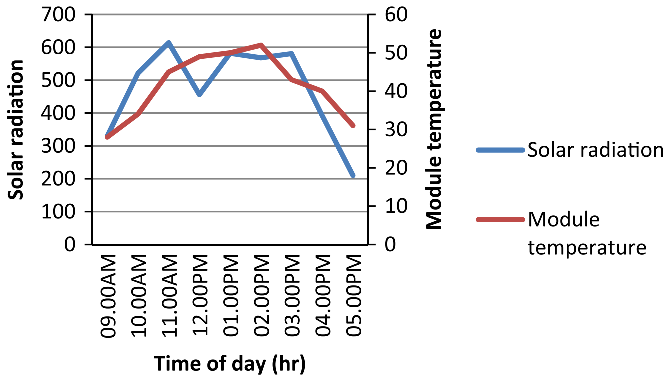

Fig. 8. Variation of solar radiation and module temperature of BISPV module for façade.

Table 4
Electrical and thermal energy of BISPV module for roof and façade.

Energy/Exergy	Time	Values in kWh (roof)	Values in kWh (facade)
Electrical energy	Daily	0.309	0.45
	Monthly	7.725	11.25
	Annually	92.7	135
Thermal energy	Daily	0.15	0.323
	Monthly	3.75	8.075
	Annually	45	96.9
Thermal exergy	Daily	0.93	1.85
	Monthly	11.16	22.2
	Annually	103.86	157.2

5. Conclusion

In this experimentation, a comprehensive analysis of energy and exergy analyses has been carried out to investigate the performance of BISPV module. The experimentation data obtained through measurements during a clear day is analysed to find the optimum temperature, which leads to maximum exergy efficiency. On the basis of practical results the following conclusions have been drawn:

- It has been found that the building integrated semitransparent photovoltaic module temperature has a great effect on the exergy efficiency.
- The exergy efficiency of a BISPV module can be improved if the heat can be removed from the BISPV module surface. There are some experimental methods for the cooling of BISPV module using flowing water on the top surface of

modules.
- The design parameters such as BISPV module area have very little effect on the exergy efficiency.
- As the environmental temperature i.e. ambient temperature increases, the exergy efficiency of BISPV module falls down.
- The exergy efficiency of BISPV module decreases as the ambient temperature increase due to increasing module temperature.
- The exergy efficiency of BISPV module increases initially with increase in solar intensity and then decreases after attaining peak point.
- Future studies should focus on modeling the efficiency of the BISPV module and exergy analysis with destruction.

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