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# Optimization and Performance Characteristics of Building Integrated Photovoltaic Thermal (BIPVT) System in Cold Climatic Conditions

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**Abstract:** Building integrated photovoltaic thermal (BIPVT) system has the potential to become a major source of renewable energy in the urban environment. In this paper, roof top has been used as the system of a building to generate higher electrical energy per unit area and to produce necessary thermal energy required for space heating. A model has been developed using basic heat transfer equations. On the basis of this model, an analysis has been carried out specifically for Indian climatic condition of Srinagar, in order to select an appropriate BIPVT system. The PV performances, electrical and thermal efficiencies, net energy gain and exergy of the building are determined. The results show that the electrical efficiency and overall exergy has been increased for the same system which was discussed earlier by changing the design parameters of the system such as velocity of air, room size, number of rows of cells etc. and other affected parameters. The electrical efficiency has been increased to 17.17% from previously 16% and overall exergy to 18.4% from previously 17.1% i.e. an overall growth of 6.8% and 7.6% respectively. Optimization of overall exergy w.r.t velocity of air and thermal coefficient has been analyzed.

**Key words:** Building integrated photovoltaic system (BIPVT), photovoltaic (PV), exergy, roof top system.

## Introduction

Energy is considered as a prime agent in the generation of wealth and a significant factor in the economic development. Today, the electricity conversion-efficiency of a silicon solar module available for commercial application is about 12-18%. The development scale of any country is measured by few parameters among which per capita consumption holds the most significant rank; with decrease in conventional energy resources and growing environmental concerns it is expected that solar energy is going to play a very significant role in future. Over the last decades a significant research on photovoltaic (PV) solar cells and modules has been carried out. More than 80% of the incoming solar energy is either reflected or absorbed as heat energy. Consequently, the working temperature of the solar cells increases considerably after prolonged operations and the cells efficiency drops significantly. By cooling the PV module with a fluid stream like air or water, the electricity produced can be improved. At the same time, the heat picked up by the fluid can be used to support space heating or service hot water system or drying of medicinal plants.

Building integrated photovoltaic (BIPV) started to become important in late 1990s. It has been considered

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as an attractive technology for building integration. Singh and Agrawal (2015) described the modelling and optimization of single channel system by genetic algorithm. Scheme proposed by Singh (2016) made a comparative study of exergy of different cities and concluded that there is an increment of 5.8 to 14.7% of exergy as compared to as proposed by Agrawal and Tiwari (2008) by soft computing technique.

Agrawal and Tiwari (2009) concluded that in terms of energy saving glazed hybrid gives better result as compared to normal PV module. Vats and Tiwari (2012) provided various data of efficiency of different types of material out of which one can select. He et al. (2006) used the hybrid photovoltaic and thermal (PVT) collector technology using water as the coolant as a solution for improving the energy performance.

Mercaldo et al. (2009) presented an analysis on architectural issues and technological developments. Building integrated photovoltaic thermal (BIPV) system appears as an exciting new technology as it merges photovoltaic and thermal systems, providing simultaneously both the electrical and the thermal energy onsite. The system integrates roof, photovoltaic, thermal and insulation into a single product. Due to sharing of resources like materials and functions in the integration, the BIPVT system becomes cheaper than that having four separate products. Moreover, the BIPVT system is installed by one team at the same time which reduces the cost. A brief description of the theory and mechanism of BIPVT systems has been presented by Ibrahim et al. (2007).

The BIPVT systems may be either semi-transparent or opaque type. The semi-transparent type systems with day lighting can be integrated with the walls, roofs and windows of the building. However the semi-transparent type systems without lighting and the opaque type systems can only be integrated with the walls and roofs of the building. The BIPVT systems integrated on the walls and windows are called façade. The detail classification of the BIPVT systems is presented in Figures 1 and 2.

Cheng et al. (2009) established a correlation between the optimal angle for the fixed BIPVT systems and the latitude of the systems site using software PVSYST (photovoltaic system). They concluded that in the northern hemisphere for a maximum radiation, the system should be south oriented having inclination with horizontal surface equal to the latitude of the system's site. Ranjan et al. (2008) found that in the northern hemisphere the semi-transparent type systems used as façade for the south walls and windows collect

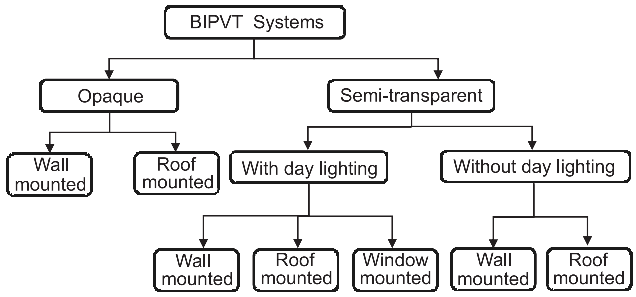



**Figure 1: Classification of BIPVT systems.**

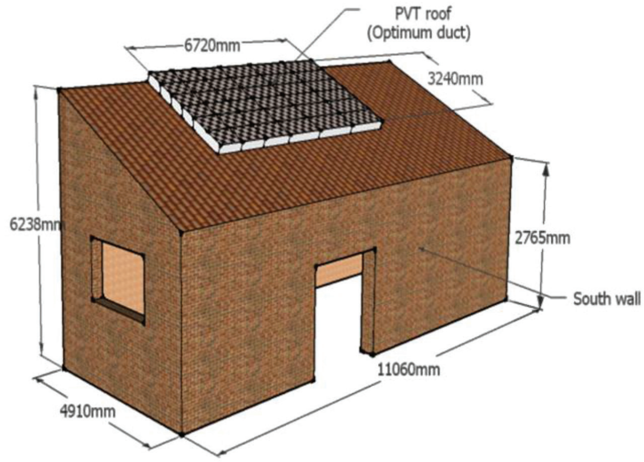



**Figure 2: Perspective view of proposed BIPVT system installed at the roof of a building.**

maximum energy, whereas the semi-transparent type systems used as façade for the north walls and windows collect minimum or no energy.

Fung and Yang (2008) presented one dimensional heat transfer model for the semi-transparent photovoltaic module used in the façade of building integrated photovoltaic systems. Zondag et al. (2002) analyzed thermal and electrical yield of a PV-thermal collector using steady 3D, 2D and 1D heat transfer modules. It is concluded that for the determination of the efficiency curves and the daily and annual yield the simple steady ID model performs satisfactorily, while the calculation time is substantially reduced in comparison to the more complicated models.

Chow et al. (2009) developed computer simulation with energy models for the façade of opaque type building integrated photovoltaic water heating system. They showed the year round thermal and cell efficiency as 37.5% and 9.39% respectively, for Hong Kong city. Anderson et al. (2009) suggested the opaque type BIPVT solar collector for walls and roofing structure

**Nomenclature**

| | |
|---|---|
| $A_{roof}$ | area of roof, $m^2$ |
| $b$ | width of the BIPVT system, m |
| $C_{air}$ | specific heat of air at constant pressure, j/kg K |
| $C_r$ | the conversion factor of the thermal power plant |
| $dx$ | elemental length, m |
| $dt$ | elemental time, s |
| $E_{out}$ | electrical energy, W h |
| $h$ | heat transfer coefficient, $W/m^2$ K |
| $h_o$ | heat transfer coefficient for outside (the room), $W/m^2$ K |
| $h_{p1}$ | non-dimensional penalty factor of PV module due to the glass cover |
| $h_{p2}$ | non-dimensional penalty factor of PV module due to the tedlar |
| $l(t)$ | solar intensity on the BIPVT system, inclined at an angle equal to the latitude of the place, $W/m^2$ |
| $K$ | thermal conductivity, W/m K |
| $L$ | length, m |
| $m_{air}$ | air mass flow rate in duct, kg/s |
| $m_r$ | air mass flow rate in room, kg/s |
| $N$ | number of sunshine hour in a day |
| $N_0$ | number of air change/h |
| $n_{pv}$ | number of rows of BIPVT system |
| $Q_u$ | useful thermal energy, W h |
| $T$ | temperature, K |
| $T_{av}$ | average temperature, K |
| $U$ | overall heat transfer coefficient, $W/m^2K$ |
| $v$ | velocity of air, m/s |
| $V$ | volume of room, $m^3$ |
| $(UA)_t$ | heat loss capacity through walls, doors and windows, W/K |

**Greek letters**

| | |
|---|---|
| α | absorptivity |
| β | packing factor |
| τ | transmissivity |
| η | efficiency |
| ρ | density, $kg/m^3$ |
| φ | efficiency correction coefficient |

**Subscripts**

| | |
|---|---|
| a | ambient |
| air | air in the duct |
| airout | air outlet from the duct |
| bs | back surface |
| bb | insulation plate |
| c | solar cell |
| ca | cell actual |
| d | door |
| daily | daily |
| E | electrical |
| eff | effective |
| $E_{TH}$ | electrical equivalent to thermal efficiency |
| G | glass top |
| hourly | hourly |
| i | insulation |
| j | integer |
| ti | tedlar to insulation |
| o | overall |
| ar | air in the room |
| ref | reference given for solar cell by manufacturer |
| T | tedlar |
| $t_{air}$ | tedlar to air |
| TH | thermal |
| u | net useful |
| w | wall |
| win | window |

of a building and made the theoretical analysis using Hottel-Whillier model and validated using experimental data of a prototype collector. Recently, Agarwal and Tiwari (2012) carried out the study using the opaque type BIPVT system fitted on the building of a laboratory at the Centre for Sustainable Technology (CST), Indian Institute of Science, Bangalore. It was concluded that the systems fitted on the roof yields a net electrical and an energy gain of 575 kWh/year and 1867 kWh/year, respectively. The present paper aims to optimize the system configurations for higher electrical and energy gain for cold climatic conditions.

## Thermal Modelling of BIPVT System

In the present analysis, the transparent type mono crystalline BIPVT systems have been proposed for the roof of the buildings under cold climatic conditions of Srinagar, India. As Srinagar is situated at 34°1′ N, 74°51′ E, the roof for fitting the BIPVT systems is south oriented inclined at an angle of 35° to the horizontal. The roof is fitted with a total of 48 BIPVT systems spread over six rows each having eight BIPVT systems covering an area 65 $m^2$. An air blower consuming 0.15 kWh is used to circulate the air through the duct at a constant mass flow rate of 1.5 kg/s. Thus, solar electric generation would eliminate the huge number of local batteries and replace the costly electricity during the peak demand. Table 1 gives the detail specifications of the building while Table 2 provides the design parameters of the BIPVT system.

**Table 1: Specification of building at Srinagar**

| | |
|---|---|
| Max. Panel voltage | 425 V |
| Efficiency | 17.1% |
| Size of room | 5580 mm × 4910 mm |
| Side wall height | South wall 2765 mm, North wall 6238 mm |
| Roof area | 11060 mm × 6144 mm |
| Roof inclination | 35° |
| Windows | 1 on east wall, 1 on west wall and 2 on north wall |

**Table 2: Design parameters of BIPVT system**

| *Parameters* | *Values* |
|---|---|
| Length of each BIPVT system | 1650 mm |
| Width of each BIPVT system | 800 mm |
| Net output of a BIPVT system | 155 W |
| Duct depth | 255 mm |
| Air flow | Single pass below tedlar |
| $C_{air}$ (J/kg K) | 1005 |
| $C_r$ | 0.38 |
| $H_0$ (W/m$^2$) | 5.7 + 3.8 × va |
| $h_i$ (W/m$^2$) | 2.8 |
| $h_T$ (W/m$^2$) | 2.8 + 3 × vair |
| $K_c$ (W/m$^2$ K) | 0.039 |
| $K_G$ (W/m$^2$ K) | 0.8 |
| $K_i$ (W/m$^2$ K) | 0.035 |
| $K_T$ (W/m$^2$ K) | 0.38 |
| $L_c$ (mm) | 0.3 |
| $L_G$ (mm) | 32 |
| $L_i$ (mm) | 10 |
| $L_T$ (mm) | 3 |
| $\alpha_c$ | 0.7 |
| $\alpha_t$ | 0.7 |
| $\beta_c$ | 0.9 |
| $\eta_c$ | 0.16 |
| $í_g$ | 0.85 |
| $\rho_a$ (kg/m$^3$) | 1.29 |

## Thermal Output

Using empirical relation given by Evans [1981], the actual electrical efficiency of the BIPVT systems is given by

$$\eta_{ca} = \eta_{ref}\,[1 - \varphi_{ref}\,(T_c - T_a)] \tag{1}$$

Quantities $\eta_{ref}$, $T_a$ and $\varphi_{ref}$ are usually given by the photovoltaic module manufacturers but they can be also obtained from flash tests. Thus, the hourly electrical output of the BIPVT systems is given by

$$E_{out} = \eta_{ca} \times I\,(t) \times bL \times n_{pv} \tag{2}$$

The conventional electrical output can be converted to an equivalent thermal output using expression given by Joshi et al. (2007) as follows

$$E_{eth} = \frac{E_{out}}{C_f} \tag{3}$$

The hourly overall thermal output of the BIPVT system can be calculated by adding hourly thermal gain of the BIPVT systems to eq. (3). Therefore,

$$Q_{hourly} = \frac{E_{out}}{C_f} + Q_u \tag{4}$$

The daily overall thermal output of the BIPVT system can be calculated by

$$Q_{daily} = \sum_{j=1}^{n} \frac{(\eta_{ca})_j \times [I(t)]_j \times bL \times \eta_{pv}}{C_f} + \sum_{j=1}^{n} (Q_u)_j \tag{5}$$

Adding daily overall thermal output for a year will give the annual overall thermal output. Overall thermal efficiency of the BIPVT system can be calculated by dividing overall thermal output to the overall thermal gain from the solar energy. Thus,

$$\eta_{TH} = \frac{\sum_{j=1}^{n} \frac{(\eta_{ca})_j \times [I(t)]_j \times bL \times \eta_{pv}}{C_f} + \sum_{j=1}^{n} (Q_u)_j}{\sum_{j=1}^{n} [I(t)]_j \times bL \times \eta_{pv}} \tag{6}$$

As there is a temperature difference between hot air coming out of the BIPVT system as a heat source and the atmospheric air as a heat sink, thermal energy can be transformed into work. The magnitude of transformable thermal energy to work is restricted by the Carnot efficiency. Thus, from the instantaneous quantity of heat $Q_u$ produced by the BIPVT system, instantaneous thermal exergy (Nayak and Tiwari, 2008) is

$$\text{Thermal Energy} = Q_u \left(1 - \frac{T_a}{T_{airout}}\right) \tag{7}$$

Therefore, the net energy gain from the BIPVT system is the sum of the electrical gain and the instantaneous thermal energy.

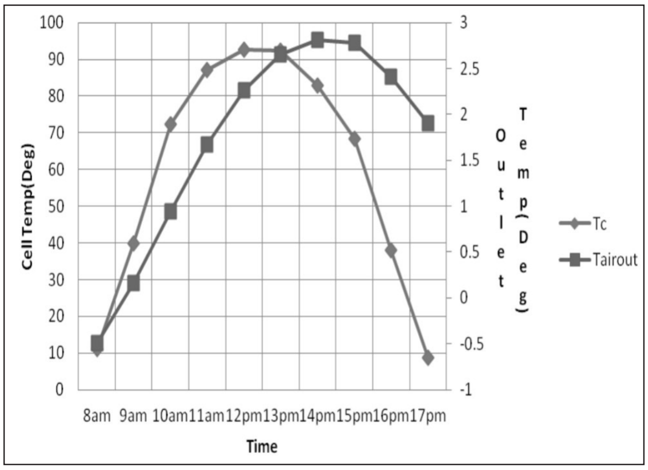



**Figure 3: Comparative study of temperature between cell and duct outlet.**

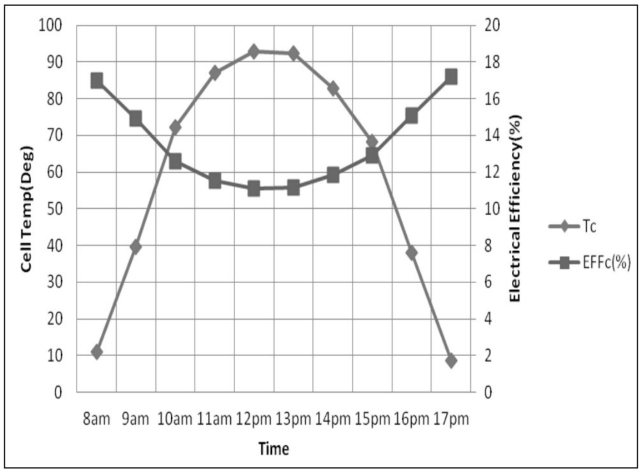



**Figure 4: Graph between cell temperature and electrical efficiency w.r.t time.**

$$\text{Net Energy Gain} = E_{out} + Q_u\left(1 - \frac{T_a}{T_{airout}}\right) \quad (8)$$

The energy balance for PV module of the BIPVT system for elemental area is given by Nayak and Tiwari (2008).

$$\begin{bmatrix} \textit{Rate of heat} \\ \textit{received by} \\ \textit{solar cell} \end{bmatrix} + \begin{bmatrix} \textit{Rate of heat} \\ \textit{received by} \\ \textit{non-packing area} \end{bmatrix} =$$

$$\begin{bmatrix} \textit{Rate of heat loss} \\ \textit{from PV mocule to} \\ \textit{air as the top loss} \end{bmatrix} + \begin{bmatrix} \textit{Rate of heat loss from} \\ \textit{pv module to} \\ \textit{back surface/tedlar} \end{bmatrix}$$

$$+ \begin{bmatrix} \textit{Rate of electricity} \\ \textit{produced} \end{bmatrix}$$

$$\tau_g\,[\alpha_c\beta_c + (1 - \beta_c)\,\alpha_T]I(t)\,bdx = [U_T(T_c - T_a) + h_T(T_c - T_{bs})]\,bdx + \eta_{ca}\,I(t)\,bdx \quad (9)$$

Simplifying Eq. (9), the expression for a solar cell temperature can be obtained as

$$T_c = \frac{h_T\,T_{bs} + U_T\,T_a + I(t)(\alpha\tau)_{eff}}{U_T + h_T} \quad (10)$$

Energy balance for back surface of the PV module, called tedlar, for elemental area *b.dx* is given by

$$\begin{bmatrix} \textit{Rate of heat gain from} \\ \textit{PV module to tedlar} \end{bmatrix} =$$

$$\begin{bmatrix} \textit{Rate of heat loss from tedlar to} \\ \textit{air side in the duct} \end{bmatrix}$$

$$h_T\,(T_c - T_{bs})\,bdx = h_{air}\,(T_{bs} - T_{air})\,bdx \quad (11)$$

Substituting $T_c$ from Eq. (10) in Eq. (11), expression for back surface temperature is obtained as

$$T_{bs} = \frac{h_{air}\,T_{air} + U_{tT}\,T_a + h_{\rho 1}I(t)(\alpha\tau)_{eff}}{U_{tT} + h_{air}} \quad (12)$$

Energy balance for air flowing in the duct of the BIPVT system for elemental area *b.dx* is given by

$$\begin{bmatrix} \textit{Rate of heat received from tedlar} \\ \textit{to air side in the duct} \end{bmatrix} =$$

$$\begin{bmatrix} \textit{Rate of heat gain by air} \\ \textit{flowing in duct} \end{bmatrix} +$$

$$\begin{bmatrix} \textit{Rate of heat loss from air} \\ \textit{through insulation} \end{bmatrix}$$

$$h_{air}\,(T_{bs} - T_{air})\,bdx = M_{air}\,C_{air}\left(\frac{dT_{air}}{dx}\right)dx + U_{bb}\,(T_{air} - T_{ar})\,bdx \quad (13)$$

On substituting $T_{bs}$ from Eqn (12) to Eqn (13) we have

$$h_{air}\left[\frac{h_{\rho 1}h_{\rho 2}I(t)(\alpha\tau)_{eff} - U_{tT}(T_{air} - T_c)}{U_{tT}\,h_{air}}\right]bdx = M_{air}C_{air}\left(\frac{dT_{air}}{dx}\right)dx + U_{bb}(T_{air} - T_{ar})bdx \quad (14)$$

By integrating Eqn (14) with boundary condition $x = 0$, $T_{air} = T_{ar}$, at $x = L$, $T_{air} = T_{airout}$, outlet air temperature of the flowing air in the duct of BIPVT system for length $L$ is given by

$$T_{airout} = \left[\frac{U_{bb}T_{ar} + U_{tair}T_a + h_{\rho1}h_{\rho2}I(t)(\alpha\tau)_{eff}}{U_{ti}}\right]\left(1 - e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + T_{ar}e^{-\frac{bU_{ti}L}{M_{air}C_{air}}} \quad (15)$$

And the average air temperature of the air flowing in the duct of the BIPVT system is given by

$$T_{air} = \left[\frac{U_{bb}T_{ar} + U_{tair}T_a + h_{\rho1}h_{\rho2}I(t)(\alpha\tau)_{eff}}{U_{ti}}\right]\left(1 - \frac{1-e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}}{\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + T_{ar}\frac{1-e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}}{\frac{bU_{ti}L}{M_{air}C_{air}}} \quad (16)$$

Rate of useful thermal energy obtained for $\eta_{pv}$ row of the BIPVT system is given by

$$Q_u = \eta_{pv} \times M_{air}\, C_{air}\,(T_{airout} - T_{ar}) \quad (17)$$

The available useful thermal energy is partly used to heat the room and rest is loss. The energy balance for space heating of building is given by

$$\eta_{pv} \times M_{air}C_{air}\left[\frac{U_{bb}T_r + U_{tair}T_a + h_{\rho1}h_{\rho2}I(t)(\alpha\tau)_{eff}}{U_{ti}} - T_{ar}\right] \times \left(1 - e^{-\frac{bU_{ti}L}{M_{air}C_{air}}}\right) + U_{bb}(T_{air} + T_{ar})A_{roof} = M_r C_{air}\left(\frac{dT_r}{dt}\right) + (UA)_t(T_{ar} - T_a) + 0.33N_oV(T_{ar} - T_a) \quad (18)$$

**Table 3.1: Variation of temperature at different places**

| $T_c$ | $T_{air}$ (duct) | $T_{airout}$ (duct outlet) | $T_r$ (room) |
|---|---|---|---|
| 11.0321 | -0.5437 | -0.4915 | -0.5959 |
| 39.742 | -0.0194 | 0.1598 | -0.1986 |
| 72.298 | 0.6211 | 0.9442 | 0.298 |
| 87.1728 | 1.281 | 1.6682 | 0.8939 |
| 92.7663 | 1.8499 | 2.2598 | 1.4401 |
| 92.2978 | 2.2433 | 2.6493 | 1.8374 |
| 82.8908 | 2.448 | 2.8109 | 2.0857 |
| 68.2848 | 2.4816 | 2.7782 | 2.185 |
| 38.0957 | 2.2473 | 2.4089 | 2.0857 |
| 8.664 | 1.868 | 1.8986 | 1.8374 |

On solving Eqn (18) we have

$$T_{ar} = \frac{f(t)}{a}(1 - e^{-at}) + T_{ri}\,e^{-at} \quad (19)$$

**Table 3.2: Variation of efficiency w.r.t cell temperature**

| *Time* | *$T_c$ (degree) Cell temp* | *Electrical efficiency (%)* |
|---|---|---|
| 8 am | 11.0321 | 17.0057 |
| 9 am | 39.742 | 14.9386 |
| 10 am | 72.298 | 12.5945 |
| 11 am | 87.1728 | 11.5236 |
| 12 noon | 92.7663 | 11.1208 |
| 1 pm | 92.2978 | 11.1546 |
| 2 pm | 82.8908 | 11.8319 |
| 3 pm | 68.2848 | 12.8835 |
| 4 pm | 38.0957 | 15.0571 |
| 5 pm | 8.664 | 17.1764 |

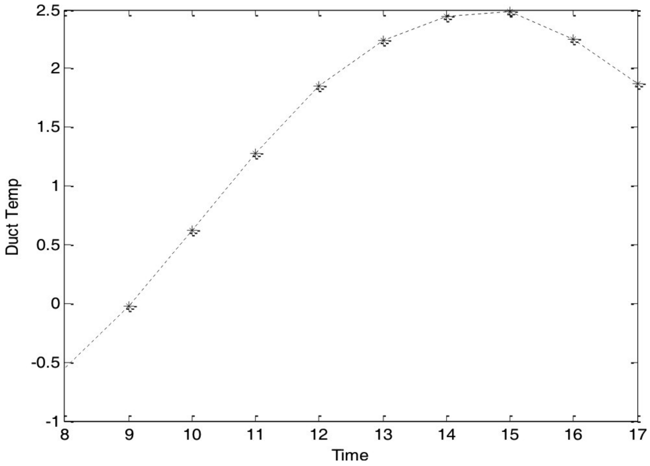
$$f(t) = \frac{1}{M_r C_{air}}\left[\{(UA)_t 0.33N_oV\}T_a + \left\{\eta_{pv}M_{air}C_{air}\left[\frac{U_{tair}T_a + h_{\rho1}h_{\rho2}I(t)(a\tau)_{eff}}{U_{ti}}\right] + \left(1 - e^{\frac{-bU_{ti}L}{M_{air}C_{air}}}\right)\right\} + U_{bb}\left\{\frac{U_{tair}T_a + h_{\rho1}h_{\rho2}I(t)(a\tau)_{eff}}{U_{ti}}\right\}\left(1 - \frac{1-e^{\frac{-bU_{ti}L}{M_{air}C_{air}}}}{\frac{bU_{ti}L}{M_{air}C_{air}}}\right)A_{roof}\right]$$

**Methodology**

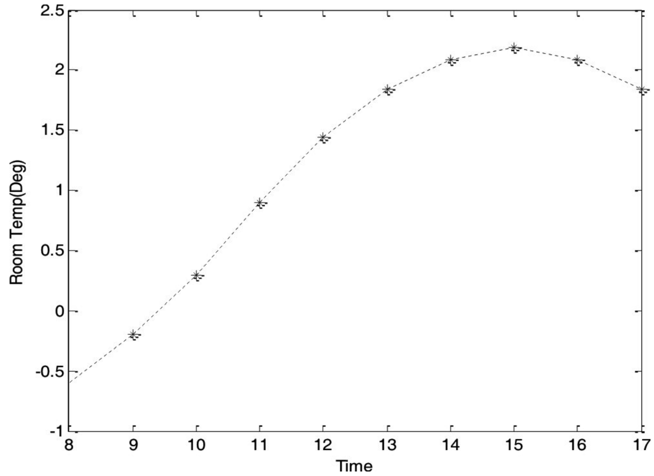
The efficiency, exergy, thermal and electrical gain have been calculated after changing the parameters related to the system.

The values have been compared with the previous one and percentage change is calculated with the use of "MATLAB-13".

These classified data are used for the present analysis. Optimization has been made to find out the exact value at which exergy is maximum w.r.t velocity of air and thermal coefficient. Analysis has been done on the basis of those values. The outlet air from one BIPVT system in a column is used as the inlet for the next




**(i) Variation of duct temperature w.r.t time.**




**(ii) Variation of room temperature w.r.t time.**

**Figure 5: Variation of duct and room temperature w.r.t time.**

BIPVT system. For the first BIPVT system, the inlet air is the mixture of circulated air of the room and the fresh ambient air. The air entering at a constant mass flow rate of 1.5 kg/s is distributed.

## Results and Discussion

The room air temperature ($T_{ar}$) is calculated with the help of Eq. (19) taking the building specifications and design parameters from Tables 1 and 2, respectively. The results are presented in Figure 5 (i) and (ii) which show that room temperature decreases one degree as compared to outlet and duct temperature. The exponential nature shows that it follows the shape of cell temperature which increases w.r.t time.

The average temperature of the back surface of the photovoltaic panel ($T_{bs}$) are calculated using Eq. (12). The solar cell temperature ($T_c$) is obtained by substituting value of $T_{bs}$ in Eq. (10). The actual cell efficiency is obtained by substituting the solar cell temperature ($T_c$) from Eq. (1). The variation of electrical efficiency is presented in Figure 4 w.r.t cell temperature which shows that at 1 pm since the cell temperature is maximum, so efficiency is minimum.

Figure 3 shows that even if the cell temperature dies out with time the outlet temp at duct continues to exist which helps to increase the overall percentage of heat content in the system. Figure 6.1 and 6.2 tells that the overall thermal gain in the system is almost 68 kWh/day whereas electrical energy gain is 25 kWh at the same time. Overall exergy gain is almost 27 kWh.

The electrical output is obtained by substituting the solar cell efficiency in Eq. (2). The useful thermal energy is calculated by substituting the values of the air outlet and room air temperatures in Eq. (17).

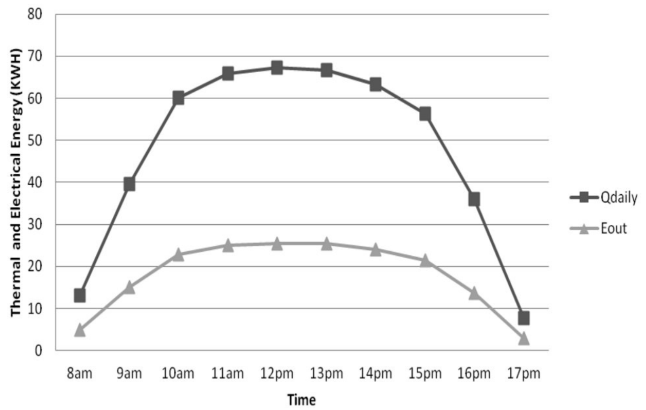



**Figure 6 (i): Comparison of electrical efficiency and exergy w.r.t time.**

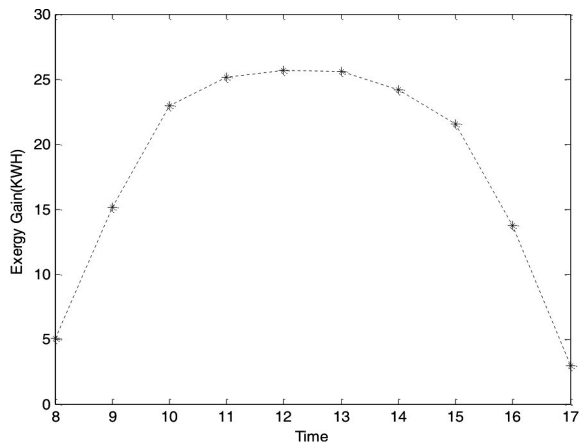



**Figure 6 (ii): Overall exergy generated w.r.t time.**

The net energy gain is determined by substituting the values of electrical output and useful thermal energy in Eq. (8).

A comparison has been made between electrical efficiency and exergy efficiency which shows that after combining the electrical and thermal energy the net electrical efficiency increases from 17.1% to 18.4% which can be shown from Figure 7.

The variation of overall exergy w.r.t velocity of air in the duct and heat transfer coefficient in the tedlar has been plotted against time which shows exergy efficiency increases w.r.t the parameters which can be shown from Figures 8.1 and 8.2 which is maximum at 2 m/sec and 7.9 w/$m^2$ respectively.

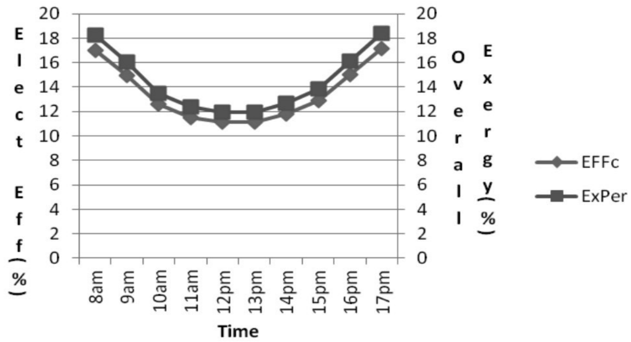



**Figure 7: Comparison of electrical efficiency and exergy w.r.t time.**

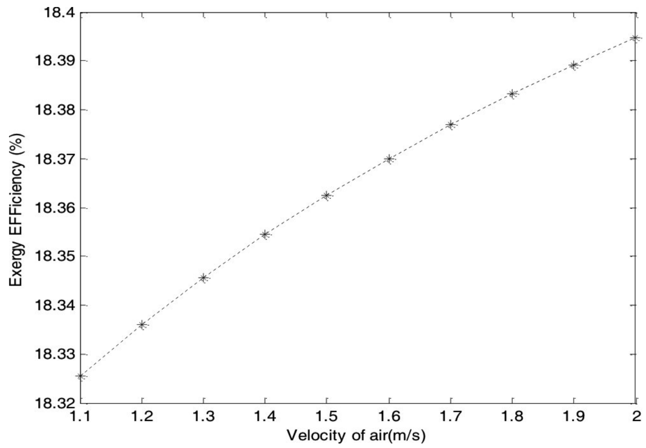



**Figure 8: Optimization of overall exergy w.r.t velocity of duct.**

## Conclusion

The data shows that the solar intensity is maximum in Srinagar at 1 pm in the month of January. If for the same system a comparison is made then it has been concluded that Srinagar gives better result as compared to Delhi i.e. almost 2% more. Comparison has also been made to know about the room temperature, duct and the outlet in Table 3.1.

The present system produces almost 67 kWh thermal energy per day as compared to 51 kWh of previous system. As far as total electrical energy is concerned it produces 25 kWh per day from 8 to 5 pm as compared to 23 kWh of previous system.

As far as efficiency is concerned this system produces 17.1% of electrical efficiency and overall exergy of 18.4% as compared to 16% and 17% of previous system.

Optimization can be understood from Figure 8 in which variation of overall exergy has been discussed w.r.t change in velocity. Maximum exergy we got when the velocity of air was at 2 m/s.

Thus from the electrical point of view, if the velocity of air flow is made constant the system is capable to produce power at a cheaper rate and hence more economical.

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## Appendix

$$(\alpha\tau)_{eff} = \tau_g[\alpha_c\beta_c + (1 - \beta_c)\,\alpha_T] - \eta_c$$

$$U_T = \left(\frac{Lg}{Kg} + \frac{1}{ho}\right)^{-1}$$

$$h_T = \left(\frac{L_T}{K_T}\right)^{-1}$$

$$h_{\rho 1} = \frac{h_T}{U_{T+h_T}}$$

$$U_{tT} = \frac{U_T \times h_T}{U_{T+h_T}} = \left(\frac{1}{h_T} + \frac{1}{U_T}\right)^{-1}$$

$$U_{bb} = \left(\frac{1}{h_{air}} + \frac{Li}{K_i} + \frac{1}{h_r}\right)^{-1}$$

$$h_{\rho 2} = \frac{h_{air}}{U_{tT+h_{air}}}$$

$$U_{tair} = \left(\frac{1}{h_{air}} + \frac{1}{U_{tT}}\right)^{-1}$$

$$U_L = (U_{bb} + U_{tair})$$

$$(UA)_t = (UA)_{t\_w} + (UA)_{t\_win} + (UA)_{t\_d}$$

$$(UA)_{t\_d} = \frac{A_d}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_d}{K_d}\right)}$$

$$(UA)_{t\_window} = \frac{A_{win}}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_{win}}{K_{win}}\right)}$$

$$(UA)_{t\_wall} = \frac{A_{wall}}{\left(\frac{1}{h_o} + \frac{1}{h_r} + \frac{L_{wall}}{K_{wall}}\right)}$$

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