# PERFORMANCE EVALUATION OF BIPVT SYSTEMS

*Presented by*

Prof. G. N. Tiwari

Centre for Energy Studies

Indian Institute of Technology (IIT) Delhi

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BAG Energy Research Society (BERS)

# Design and Fabrication of BIPVT

The system examined in this study is unique in a number of ways. Unlike many of the systems that have been proposed, this system is directly integrated into the roof of a building.

A standing seam and troughed sheet roofs typically from aluminium is made, although stainless steel could be used. They are shaped such that it gives the roof product stiffness, strength and when assembled are weather proof.

# BIPVT System Modules

The BIPVT system modules were made by BHEL, Bangalore with 72 monocrystalline solar cells connected in series with two redundantly interconnected strings. Cells are laminated in ultra-violet stabilized polymer (EVA) and mounted behind a high transmission toughened glass surface. Lamination process using Tedlar-Polyster-Tedlar, EVA, scrim and edge sealing of laminate by aluminium sealant tape having acrylic adhesive provides complete sealing against extreme temperature and weather conditions. The PV module is framed on Anodized aluminium. PV modules are manufactured to stringent quality specifications and tested to withstand adverse environmental conditions. It conforms to the CEI/IEC 61215 standard.

# Photovoltaic Modules Specification

| | |
|---|---|
| Manufacturer, Name | BHEL. Bangalore |
| Name | L24150 |
| Cell Technology | MonoCrystalline Silicon |
| Length of PV module | 1600mm (1594 mm) |
| Width of PV module | 790 mm (789 mm) |
| Height | 40 mm |
| Weight | 15 kg |
| Number of cells in a module | 72 |
| Nominal output of a module | 150 Watt |
| Max. Panel Voltage | 420 V |
| Efficiency | 16% |
| Price | $4 to $4.20 per watt. |

# Roof of the Experimental Laboratory

The roof of the experimental laboratory is made inclined 15° towards south for fitting the PV modules. On the roof there is a provision of fitting 48 photovoltaic modules, 8 in series and 6 in parallel.

Electrical output of BIPVT is used to charge battery of 24 volt efficiently in virtually any climate and also it is connected to the power grid. Thus, it replace the highest cost electricity during times of peak demand and eliminate the need for huge number of local battery power.

# Building Specification

| | |
|---|---|
| Size of room 1 | 5580 × 5478 mm |
| Size of room 2 | 4582 mm × 5478 mm |
| Side wall height (south, north) | 2765 mm, 4355 mm |
| Roof area | 11060 mm × 6144 mm |
| Effective roof area | 9600 mm × 6144 mm |
| Roof inclination | 15° |
| Flow | Single pass below tedlar |
| Duct depth | 250 mm |
| Overall dimensions of module | 9600 mm × 6320 mm |
| Windows | 1 on east wall,<br>1 on west wall and<br>4 on north wall |

# Solar Radiation and Climatic Condition Data

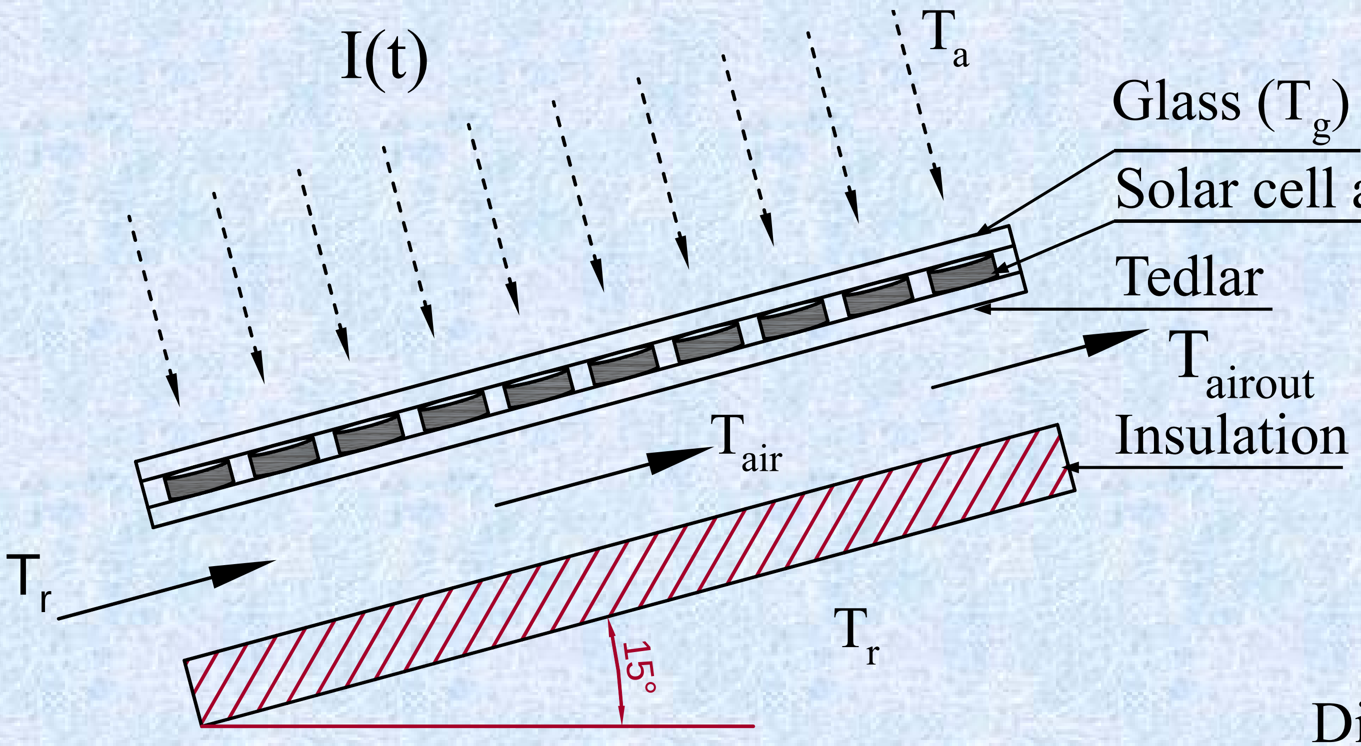
Data of different zones of India were obtained from Indian Metrological Department (IMD), Pune for 11 years. Joshi and Tiwari (2007) classified into 4 climatic conditions depending upon the ratio of daily diffuse to daily global radiations and number of sunshine hour. Classified data were used for analysis.

| Type- days | ratio of daily diffuse to daily global radiation | sunshine hours |
|---|---|---|
| A- clear days (blue sky) | $\leq 0.25$ | $\geq 9$ hrs |
| B- Hazy days (fully) | 0.25 - 0.50 | 7 - 9 hrs |
| C- Hazy and cloudy (partially) days | 0.50 - 0.75 | 5 - 7 hrs |
| D- cloudy days (fully) | $\geq 0.75$ | $\leq 5$ hrs |

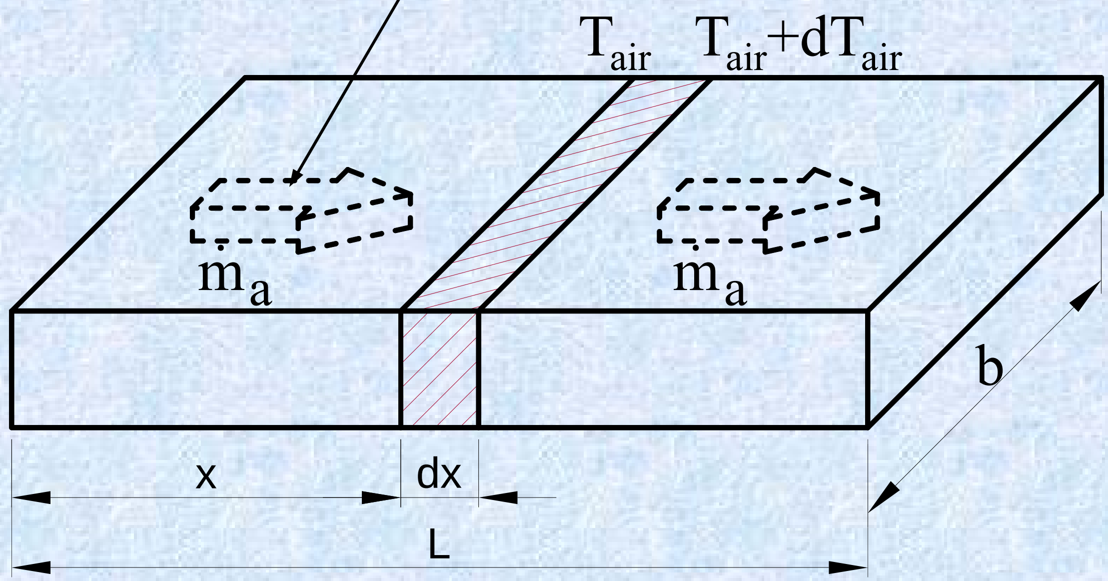
# Thermal Modelling Assumptions

In order to write the energy balance equation for each component of BIPVT system, the assumptions are as follows:

- The system is in quasi-steady-state condition.
- The specific heat of the air remains constant. It does not change with rise in the temperature of air.
- The transmissivity of EVA is approximately 100 percent.
- The temperatures of the glass cover, solar cells, tedlar, duct and insulation vary only in the direction of flow of air.
- The side losses from the system are negligible, and
- The airflow through duct is uniform for the forced mode of operation for streamline flow.




Cross section view of BIPV system




An elementary area b.dx shows flow pattern of air

# Energy balance for PV module for the elementary area b.dx

$$\tau_G \left[ \alpha_c \ I(t)\ \beta_c + (1-\beta_c)\ \alpha_T \ I(t) \right] bdx =$$ Eq. (1)

$$\left[ U_T \ (T_c - T_a) + h_T \ (T_c - T_{bs}) \right] bdx + \eta_c \tau_G \ I(t)\ \beta_c \alpha_c \ bdx$$

where, $U_T = \left( \frac{L_G}{K_G} + \frac{1}{h_o} \right)^{-1}$ and $h_T = \left( \frac{L_T}{K_T} \right)^{-1}$

Simplifying the above equation, the expression for a solar cell temperature can be obtained as

$$T_c = \frac{h_T T_{bs} + U_T T_a + I(t) (\alpha\tau)_{eff}}{U_T + h_T}$$ Eq. (2)

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

# Energy balance for back surface of the tedlar for elementary area b.dx

$$h_T \,(T_c - T_{bs})\, b\, dx = h_{air}\,(T_{bs} - T_{air})\, b\, dx$$ Eq. (3)

Substituting $T_c$ from Eq. (2) in the above equation, expression for back surface temperature is obtained as

$$T_{bs} = \frac{h_{air}\, T_{air} + U_{tT}\, T_a + h_{p1}\, I(t)(\alpha\tau)_{eff}}{U_{tT} + h_{air}}$$ Eq. (4)

where, penalty factor due to presence of solar cell material, tedlar and EVA is

$$h_{p1} = \frac{h_T}{U_T + h_T} \quad \text{and} \quad U_{tT} = \frac{U_T \times h_T}{U_T + h_T} = \left(\frac{1}{h_T} + \frac{1}{U_T}\right)^{-1}$$

# Energy balance for air flowing in duct for elementary area b.dx

$$h_{air}(T_{bs} - T_{air})b\,dx = \dot{m}_{air}C_{air}\left(\frac{dT_{air}}{dx}\right)dx + U_{bb}\,(T_{air} - T_r)b\,dx \qquad \text{Eq. (5)}$$

where, overall heat transfer for insulation plate

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

On substituting $T_{bs}$ from Eqs. (4) in (5) we have

$$h_{air}\left[\frac{h_{p1}\;I(t)(\alpha\tau)_{eff} - U_{tT}(T_{air} - T_a)}{U_{tT} + h_{air}}\right]b\,dx =$$

$$\dot{m}_aC_a\left(\frac{dT_{air}}{dx}\right)dx + U_{bb}\,(T_{air} - T_r)b\,dx$$

$$\text{or,}\quad \left(\frac{dT_{air}}{dx}\right) + \frac{b\,U_L}{\dot{m}_a C_a} T_{air} = \frac{b}{\dot{m}_a C_a}\left[U_{bb} T_r + U_{tair}\; T_a + h_{p2} h_{p1}\; I(t)(\alpha\tau)_{eff}\right]$$

Eq. (6)

where, penalty factor due to presence of interference between tedlar and the air through duct is

$$h_{p2} = \frac{h_{air}}{U_{tT} + h_{air}} \qquad U_{tair} = \frac{U_{tT} \times h_{air}}{U_{tT} + h_{air}} = \left(\frac{1}{h_{air}} + \frac{1}{U_{tT}}\right)^{-1}$$

$$\text{and}\quad U_L = (U_{bb} + U_{tair})$$

On integrating (6) with an initial condition at x = 0, $T_{air} = T_r$, the outlet air temperature ($T_{airout}$) of the flowing air below the tedlar for length L, is given by

$$T_{airout} = T_{air}\big|_{x=L} =$$

$$\left[\frac{U_{bb}\; T_r + U_{tair}\; T_a + h_{p2} h_{p1}\; I(t)(\alpha\tau)_{eff}}{U_L}\right]\left(1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}\right) + T_r\; e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}$$

Eq. (7)

And the average air temperature of the flowing air below the tedlar over the length of air duct below the PV module is given by

$$\bar{T}_{air} = \left[\frac{U_{bb}T_r + U_{tair}T_a + h_{p2}h_{p1}\ I(t)(\alpha\tau)_{eff}}{U_L}\right] \times$$

$$\left(1 - \frac{1 - e^{-\frac{b\ U_L}{\dot{m}_a C_a}L}}{\frac{b\ U_L}{\dot{m}_a C_a}L}\right) + T_r\ \frac{1 - e^{-\frac{b\ U_L}{\dot{m}_a C_a}L}}{\frac{b\ U_L}{\dot{m}_a C_a}L}$$

The rate of useful thermal energy obtained from the BIPVT system is obtained as

$$\dot{Q}_u = n_{pvt} \times \dot{m}_a C_a (T_{airout} - T_r)$$

$$= n_{pvt}\dot{m}_a C_a \left[\frac{U_{bb}T_r + U_{tair}T_a + h_{p2}h_{p1}I(t)(\alpha\tau)_{eff}}{U_L} - T_r\right]\left(1 - e^{-\frac{b\ U_L}{\dot{m}_a C_a}L}\right)$$

The available useful thermal energy is used to heat the room and a part of that is lost. The energy balance for the space heating of the building is given by

$$n_{pvt} \times \dot{m}_a C_a \left[ \frac{U_{bb} T_r + U_{tair} T_a + h_{p2} h_{p1} I(t) (\alpha\tau)_{eff}}{U_L} - T_r \right] \left( 1 - e^{-\frac{b\, U_L L}{\dot{m}_a C_a}} \right)$$

$$+U_{bb} \left( \bar{T}_{air} - T_r \right) A_{roof} = M_a C_a \left( \frac{dT_r}{dt} \right) + (UA)_t \left( T_r - T_a \right) + 0.33\ N_o V \left( T_r - T_a \right)$$

Where overall heat transfer coefficient of the room surface $(UA)_t = (UA)_{t\_w} + (UA)_{t\_win} + (UA)_{t\_d}$ is given by

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

$$(UA)_{t\_wall} = \frac{A_w}{\left( \frac{1}{h_o} + \frac{L_w}{K_w} + \frac{1}{h_r} \right)}$$

On solving (10) we have

$$\left(\frac{dT_r}{dt}\right)+\frac{1}{M_aC_a}\left[\begin{array}{l}\left\{(UA)_t+0.33\,N_oV\right\}-\left\{n_{pvt}\times\dot{m}_aC_a\left(\frac{U_{bb}}{U_L}-1\right)\left(1-e^{-\frac{b\,U_L}{\dot{m}_aC_a}L}\right)\right\}\\ \qquad -U_{bb}\left\{\frac{U_{bb}}{U_L}\left(1-\frac{1-e^{-\frac{b\,U_L}{\dot{m}_aC_a}L}}{\frac{b\,U_L}{\dot{m}_aC_a}L}\right)+\frac{1-e^{-\frac{b\,U_L}{\dot{m}_aC_a}L}}{\frac{b\,U_L}{\dot{m}_aC_a}L}-1\right\}A_{roof}\end{array}\right]T_r$$

$$=\frac{1}{M_aC_a}\left[\begin{array}{l}\left\{(UA)_t+0.33\,N_oV\right\}T_a+\left\{n_{pvt}\times\dot{m}_aC_a\left[\frac{U_{tair}T_a+h_{p2}h_{p1}I(t)(\alpha\tau)_{eff}}{U_L}\right]\left(1-e^{-\frac{b\,U_L}{\dot{m}_aC_a}L}\right)\right\}\\ \qquad +U_{bb}\left\{\frac{U_{tair}T_a+h_{p2}h_{p1}I(t)(\alpha\tau)_{eff}}{U_L}\right\}\left(1-\frac{1-e^{-\frac{b\,U_L}{\dot{m}_aC_a}L}}{\frac{b\,U_L}{\dot{m}_aC_a}L}\right)A_{roof}\end{array}\right]$$

On integrating (11) with an initial condition at $t = 0$, $T_r = T_{ri,}$ the room air temperature ($T_r$) is given by

$$T_r = \frac{f(t)}{a}\left(1 - e^{-at}\right) + T_{ri}\, e^{-at}$$ where,

$$a = \frac{1}{M_a C_a}\left[\begin{array}{l} \left\{(UA)_t + 0.33\, N_o V\right\} - \left\{n_{pvt} \times \dot{m}_a C_a \left(\frac{U_{bb}}{U_L} - 1\right)\left(1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}\right)\right\} \\ \qquad - U_{bb}\left\{\frac{U_{bb}}{U_L}\left(1 - \frac{1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}}{\frac{b\,U_L}{\dot{m}_a C_a} L}\right) + \frac{1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}}{\frac{b\,U_L}{\dot{m}_a C_a} L} - 1\right\} A_{roof} \end{array}\right]$$

$$f(t) = \frac{1}{M_a C_a}\left[\begin{array}{l} \left\{(UA)_t + 0.33\, N_o V\right\} T_a + \left\{n_{pvt} \times \dot{m}_a C_a \left[\frac{U_{tair} T_a + h_{p2} h_{p1} I(t) (\alpha\tau)_{eff}}{U_L}\right]\left(1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}\right)\right\} \\ \qquad + U_{bb}\left\{\frac{U_{tair} T_a + h_{p2} h_{p1} I(t) (\alpha\tau)_{eff}}{U_L}\right\}\left(1 - \frac{1 - e^{-\frac{b\,U_L}{\dot{m}_a C_a} L}}{\frac{b\,U_L}{\dot{m}_a C_a} L}\right) A_{roof} \end{array}\right]$$

# Thermal and Electrical Output

Thus, useful heat

$$\dot{Q}_u = n_{pvt} \times \dot{m}_a C_a \left(T_{airout} - T_r\right)$$

$$\dot{Q}_u = n_{pvt} \times \dot{m}_a C_a \left[ \frac{U_{bb} T_r + U_{tair} T_a + h_{p2} h_{p1} I(t) \left(\alpha\tau\right)_{eff}}{U_L} - T_r \right] \left( 1 - e^{-\frac{b\, U_L L}{\dot{m}_a C_a}} \right)$$

Actual efficiency of the cell

$$\eta_{ca} = \eta_c \times \left[1 - 0.0045\left(T_c - 25\right)\right]$$

Electrical output = actual cell efficiency × solar insolation

$$= \eta_c \times I\left(t\right) \times bL \times \text{effcell} \times \text{number of hours}$$

# Electrical and Thermal Efficiencies

Electrical efficiency of BIPVT system

$$\eta_E = \frac{\sum_{i=1}^{T} \eta_{ca} I(t) bL}{\sum_{i=1}^{T} I(t) bL}$$

Thermal efficiency of the BIPVT system

$$\eta_{TH} = \frac{\text{Net Thermal Output}}{\text{Net Solar Insolation}} = \frac{\sum_{i=1}^{T} \dot{Q}_u}{\sum_{i=1}^{T} I(t) bL}$$

If the conversion factor of the thermal power plant is taken into account, than the overall thermal efficiency of the BIPVT system is given by

$$\eta_o = \frac{\eta_E}{0.38} + \eta_{TH}$$

# Exergy analysis

The exergy analysis is based on the second law of thermodynamics, which includes accounting the total exergy inflow, exergy outflow and exergy destructed from the system. The general exergy balance for a BIPVT system can be written as,

$$\sum_{j=1}^{N} \dot{E}x_{in} - \sum_{j=1}^{N} \dot{E}x_{out} = \sum_{j=1}^{N} \dot{E}x_{dest}$$

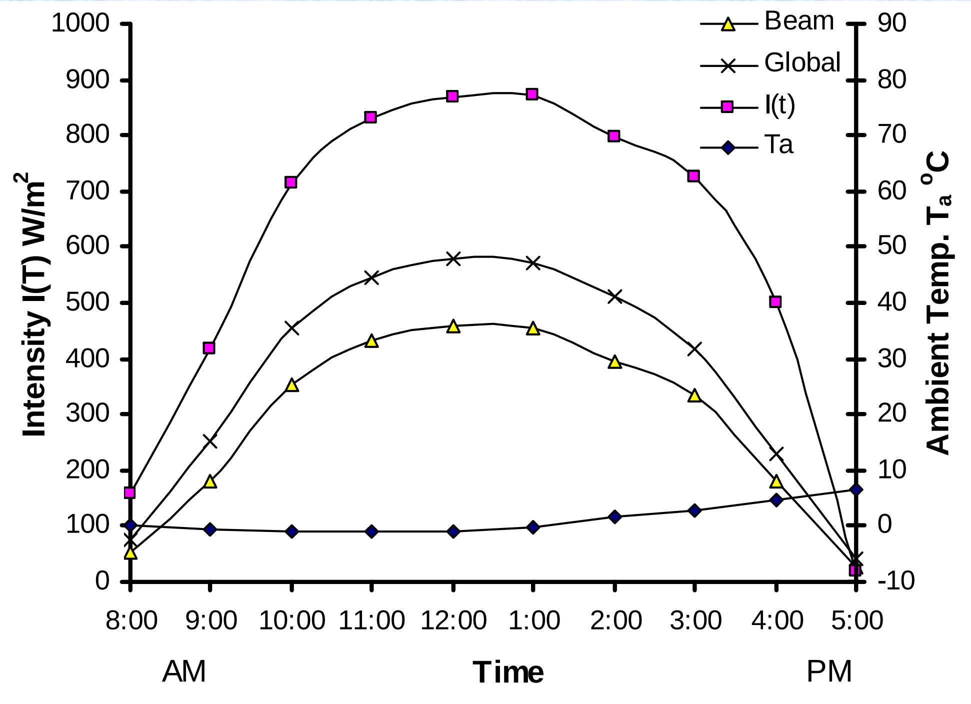
$$\dot{E}x_{in} = I(t) \times \left[ 1 - \frac{4}{3}\left\{\frac{T_a}{T_s}\right\} + \frac{1}{3}\left\{\frac{T_a}{T_s}\right\}^4 \right] \times bl \times n_{pv}$$

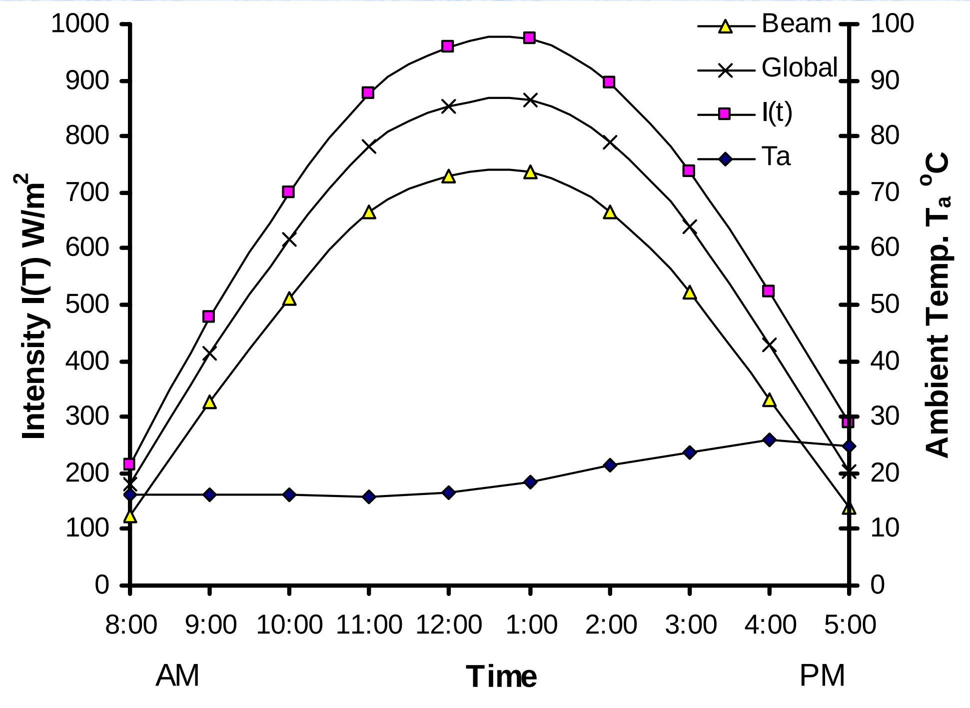
$$\dot{E}x_{out} = \dot{E}x_{TH} + \dot{E}x_{Elec}$$

$$\dot{E}x_{TH} = \left(\dot{Q}_u\right)\left\{1 - \frac{T_a}{T_{airout}}\right\}$$

$$\dot{E}x_{Elec} = \eta_{ca} I(t) bL \times \mathrm{n_{pv}}$$

# Results and Discussion




Variation of beam radiation, global radiation, intensity of light I(t) and ambient temp. (Ta) with time for a typical day in January (a) for Srinagar climate (b) for Bangalore climate.

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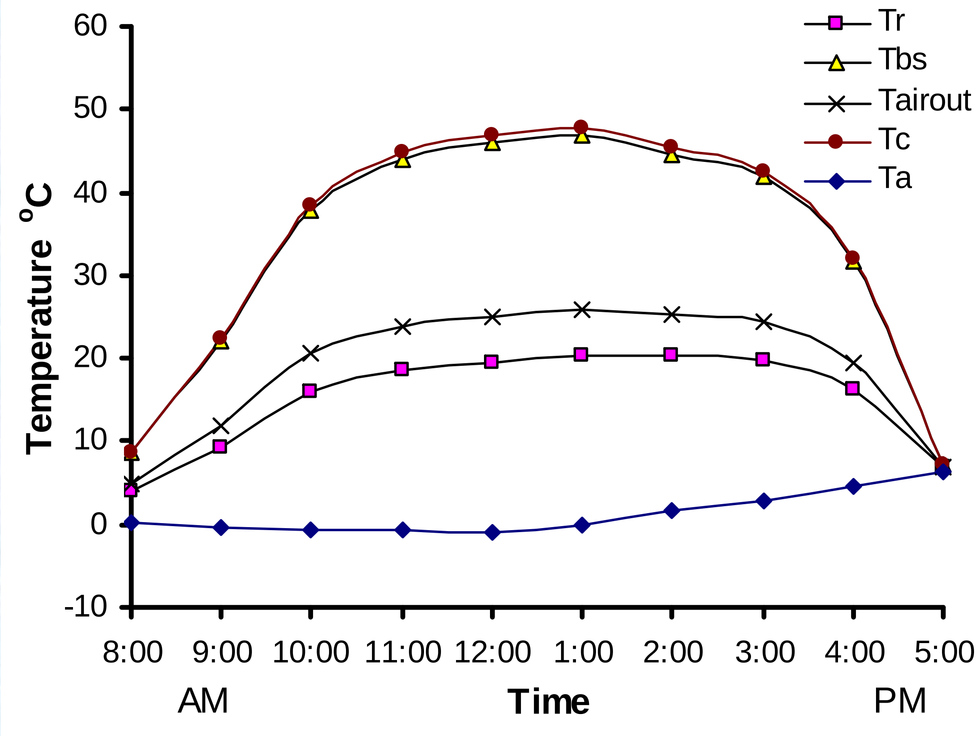


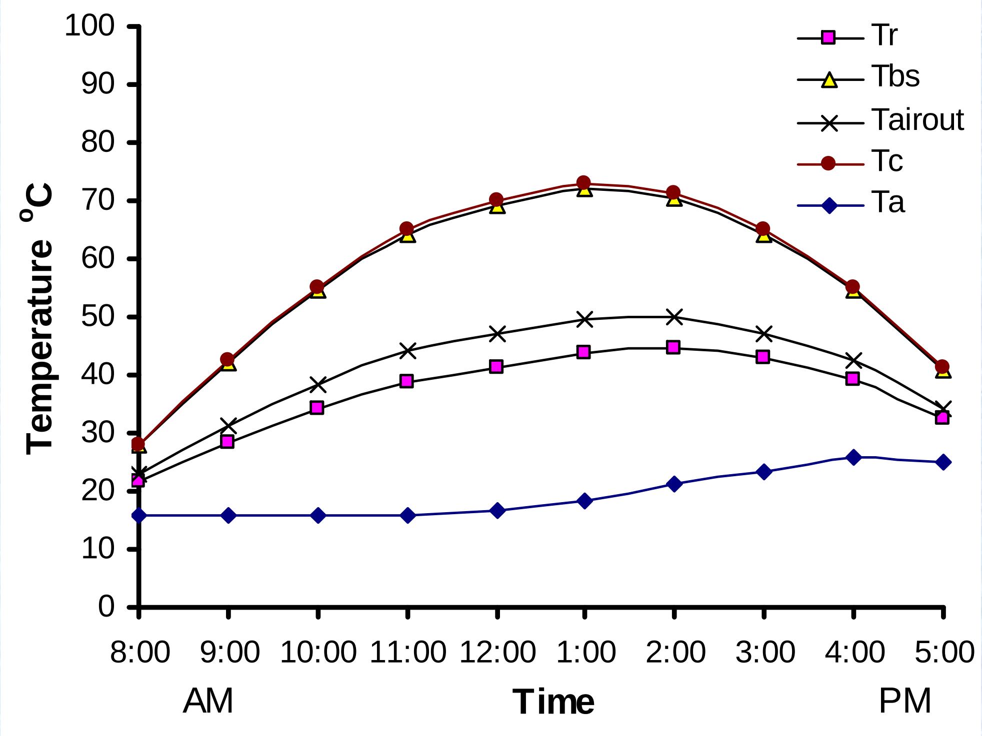


Variation of solar cell temp., back surface temp., air outlet temp., room temp. and ambient temp. with time for a typical day in January (a) for Srinagar (b) for Bangalore

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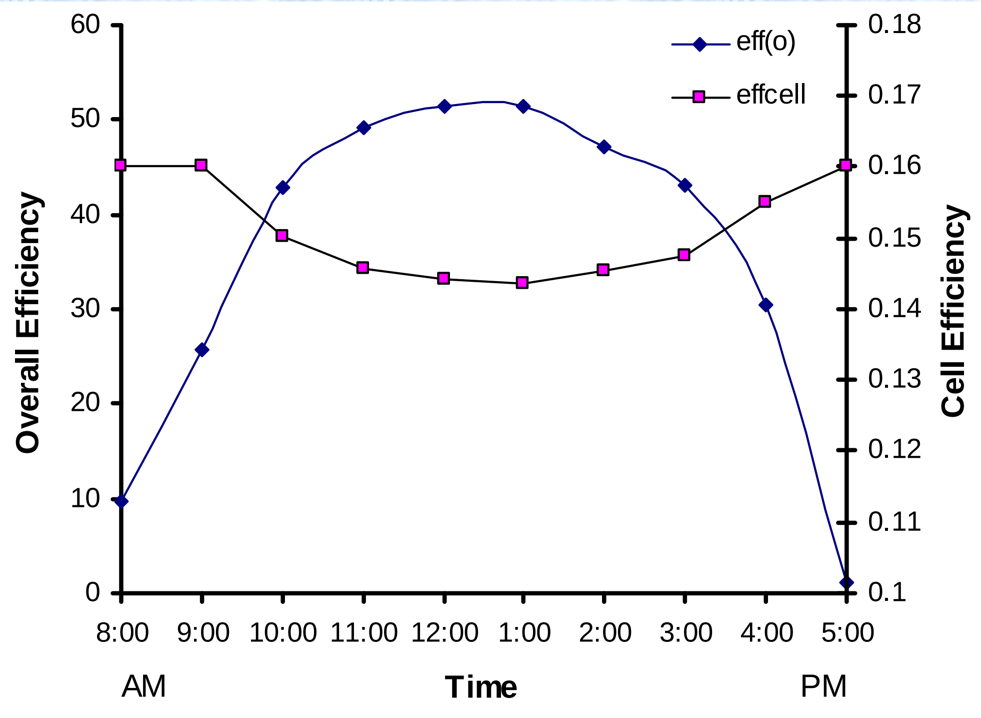


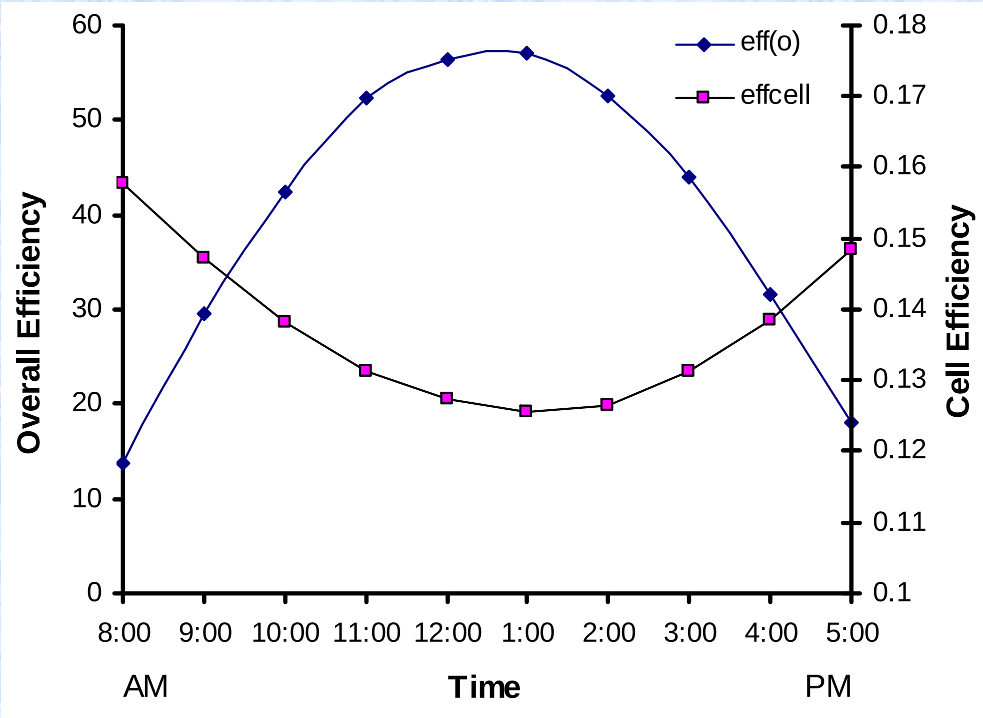


Variation of cell efficiency and overall efficiency with time for a typical day in January (a) for Srinagar (b) for Bangalore climate

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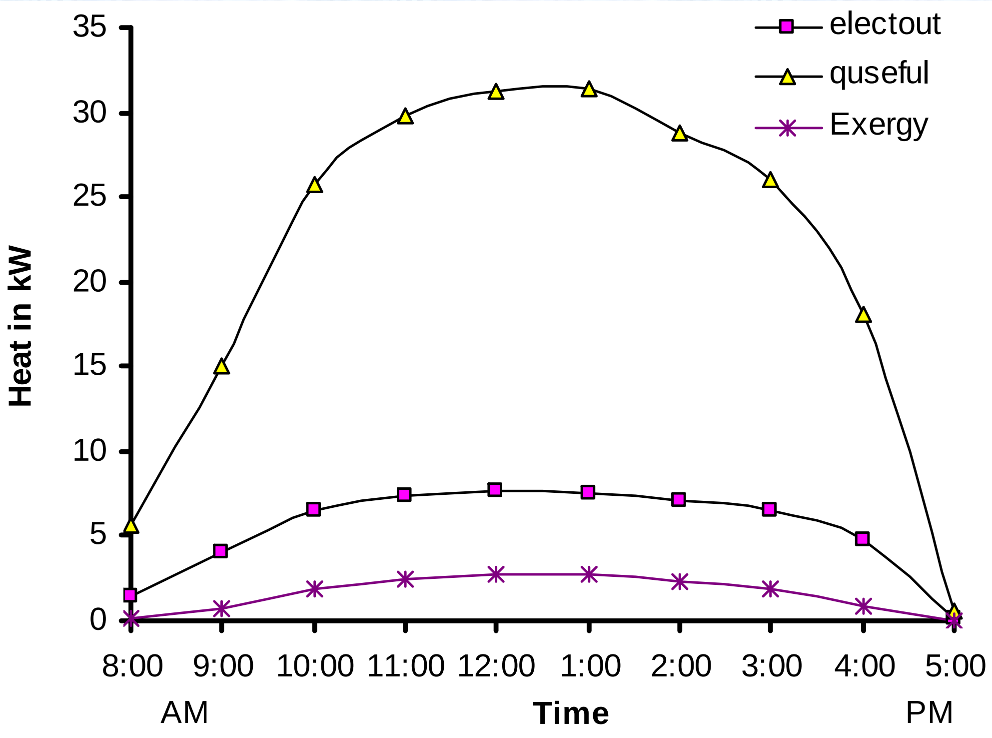


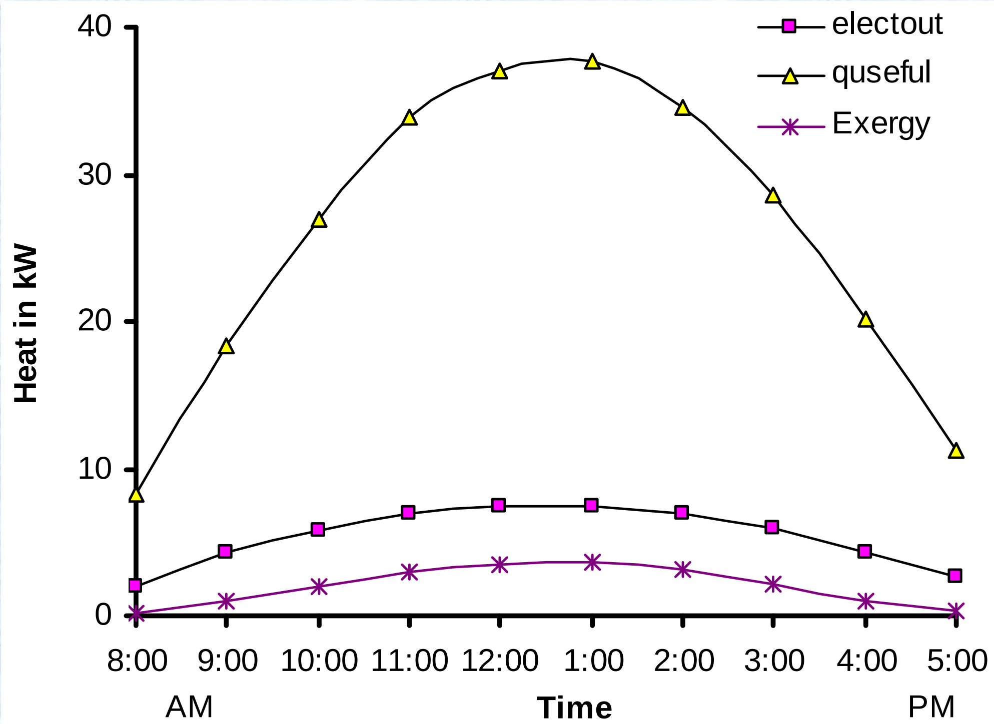


Variation of electrical output, useful heat and exergy with time for a typical day in January (a) for Srinagar (b) for Bangalore climate

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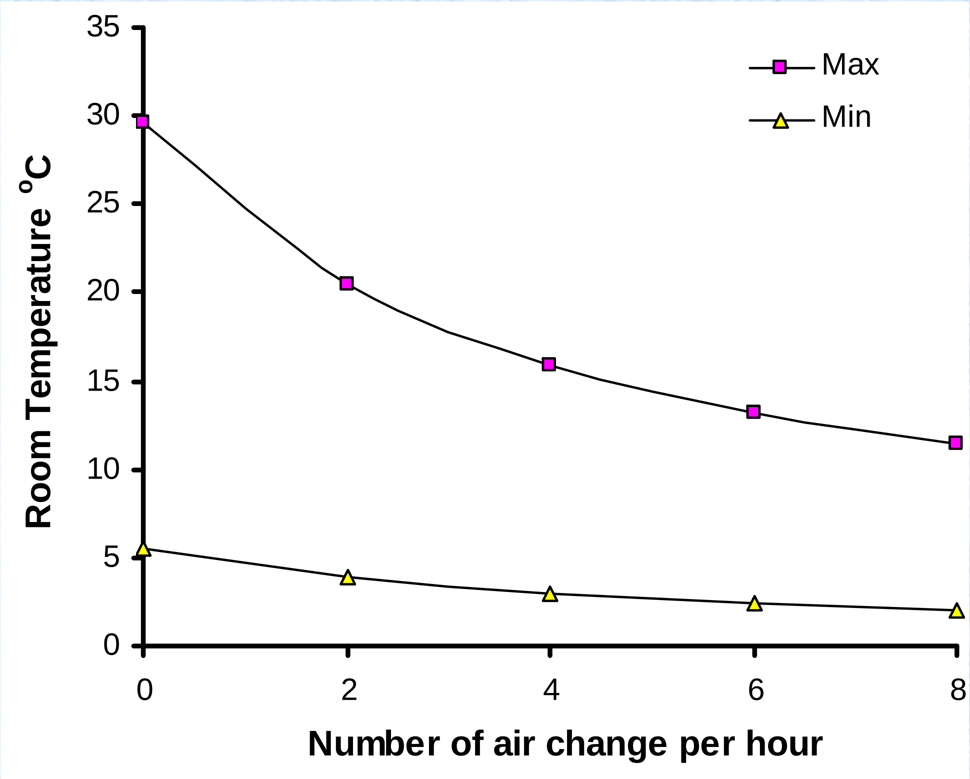


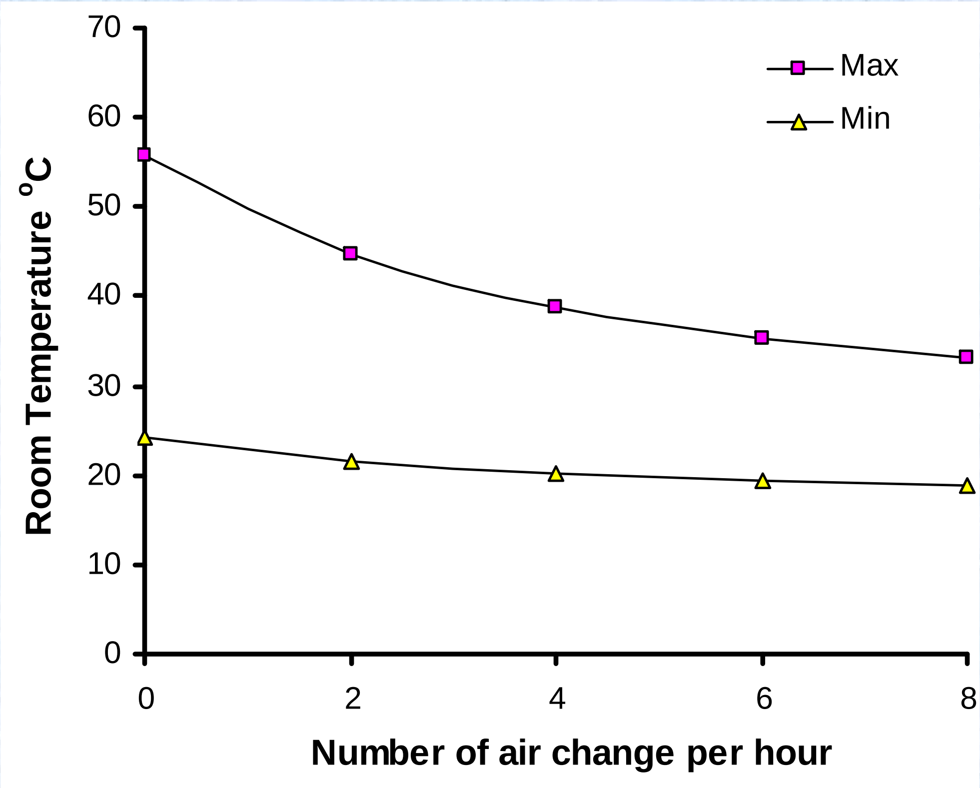


Minimum and maximum values of room temperature for different air change per hour (a) for Srinagar climate (b) for Bangalore climate

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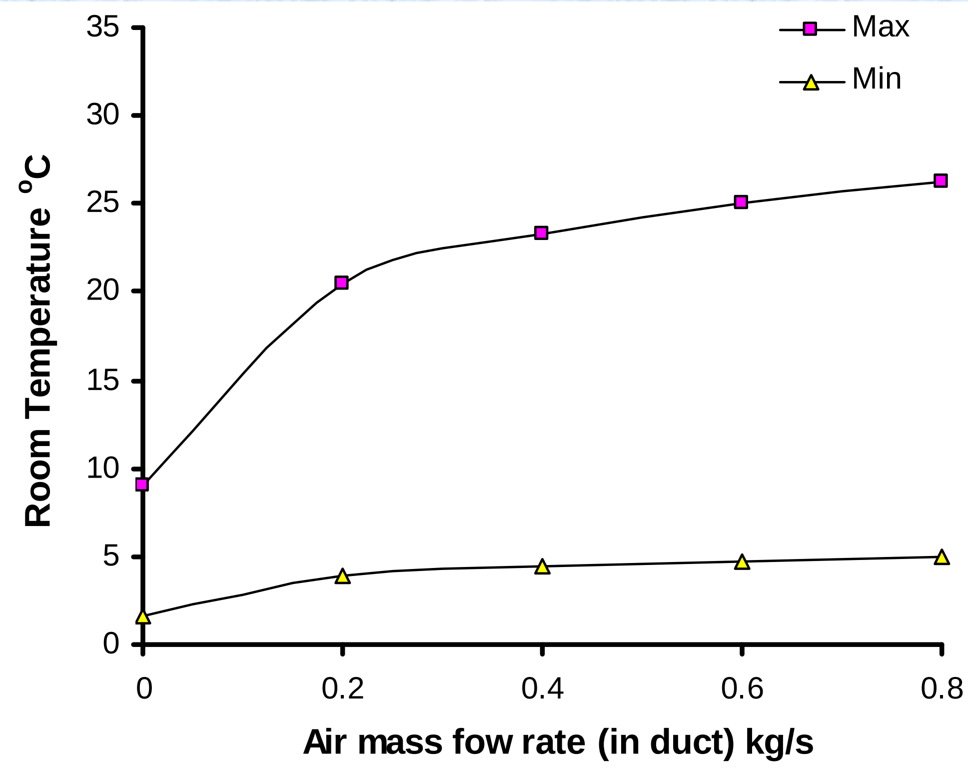


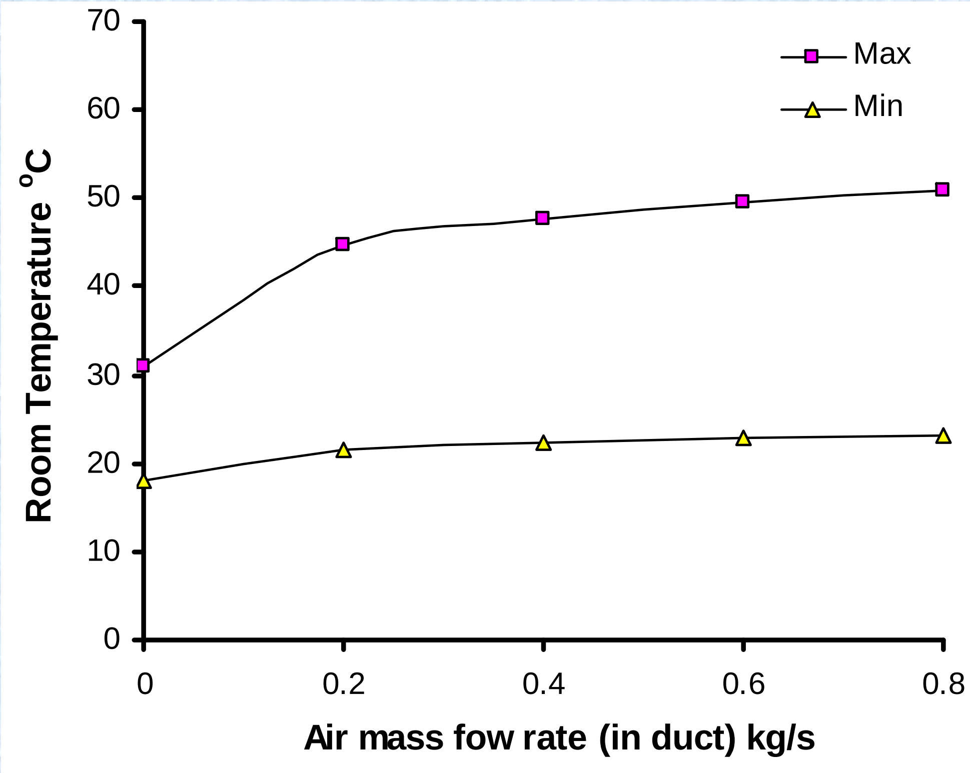


Minimum and maximum room temperature for different air mass flow rate (a) for Srinagar climate (b) for Bangalore climate

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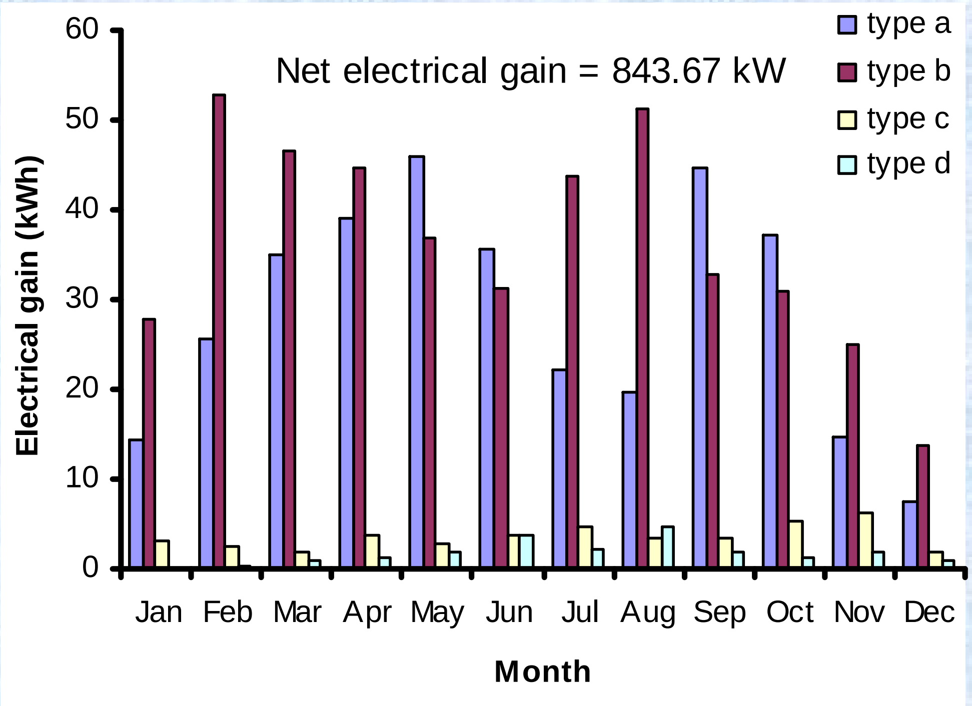


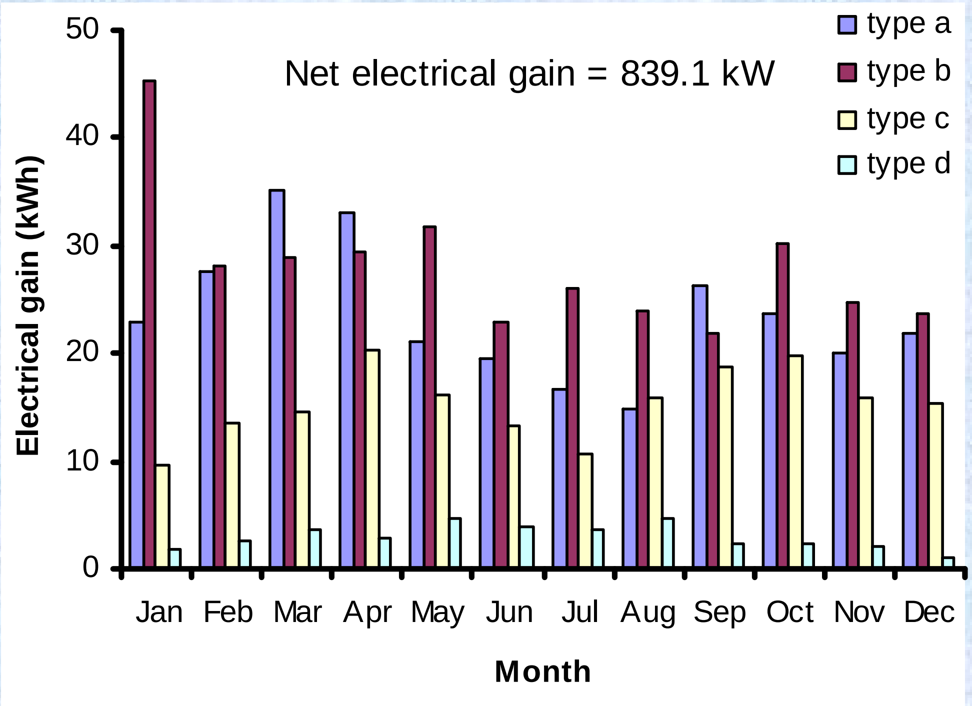


Electrical (a) for Srinagar condition (b) for Bangalore condition

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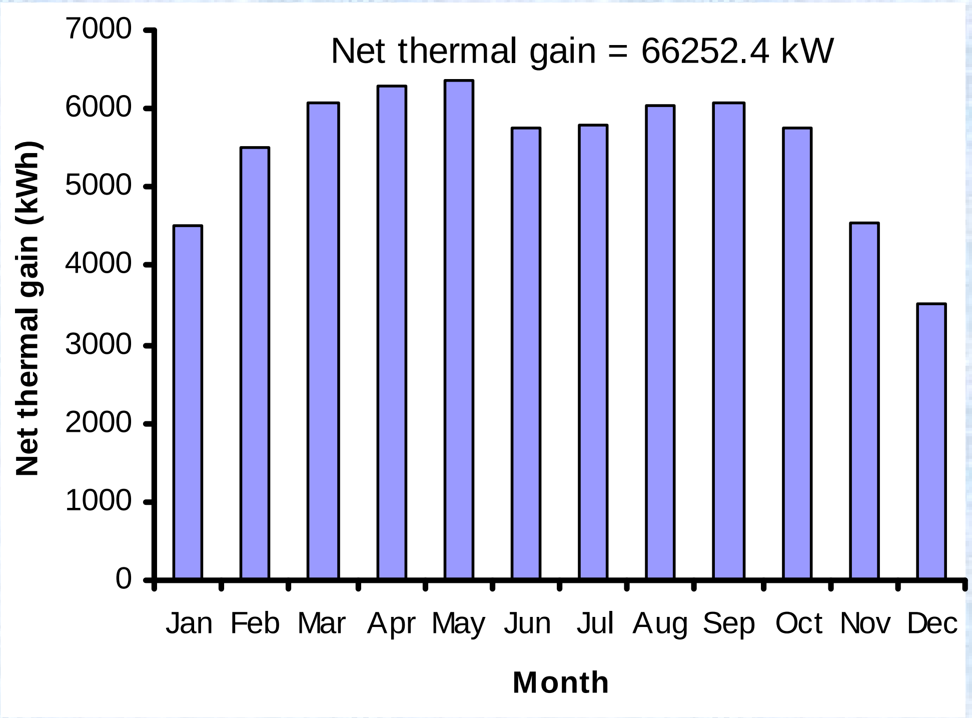


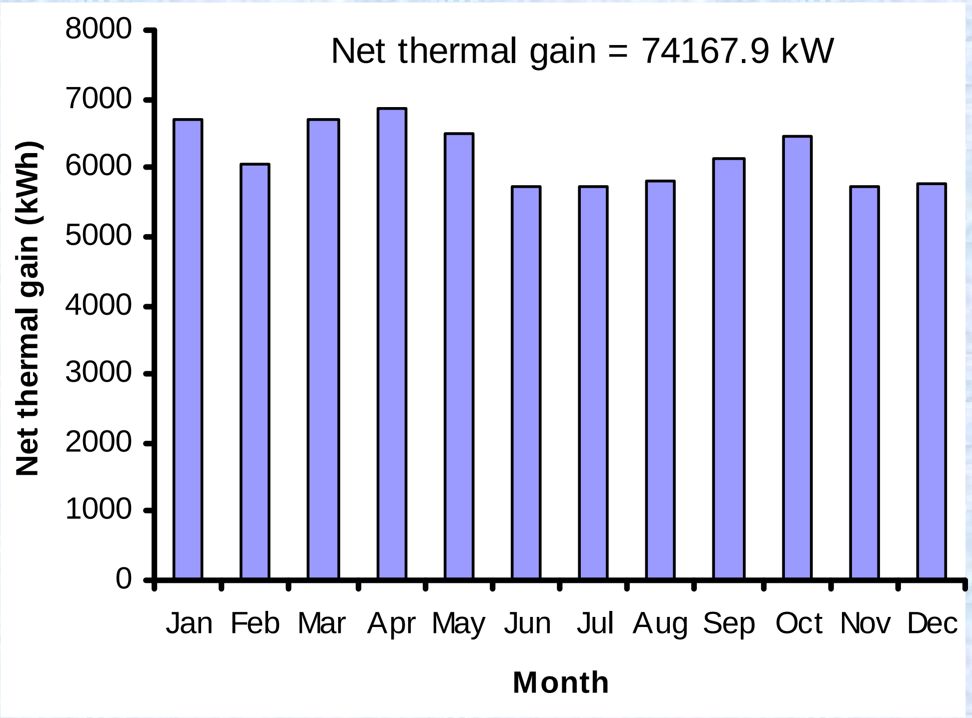


Thermal Gain (a) for Srinagar climate (b) for Bangalore climate

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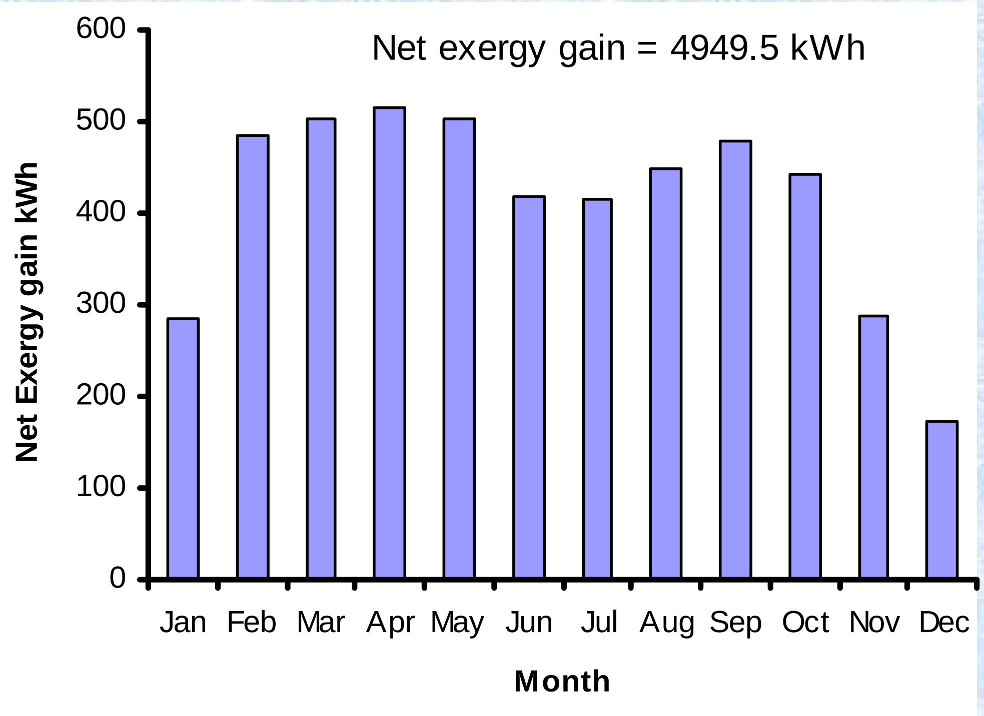


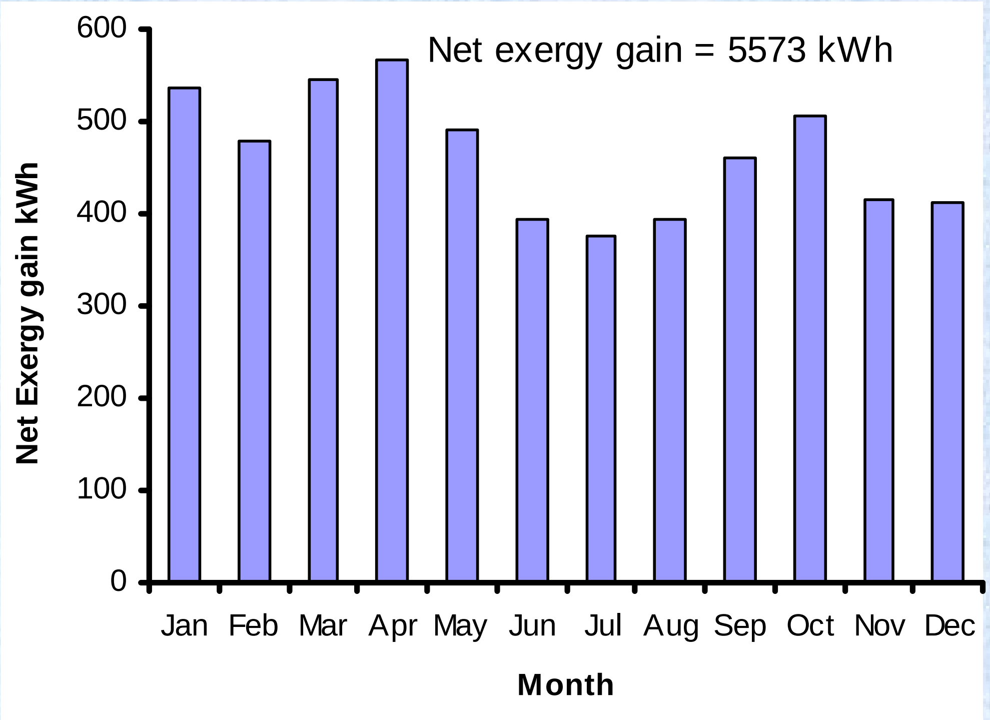


Exergy gain (a) for Srinagar climate (b) for Bangalore climate

# Conclusions

The electrical gain, thermal gain, exergy gain and net exergy gain of the BIPVT system in comparison to BIPV system for a year at Srinagar are 843 kW, 66252 kW, 4401 kW and 5245 kW respectively and at Bangalore 839 kW, 74167 kW, 5029 kW and 5868 kW respectively for an effective area of 60.672 $m^2$.

The increase in the number of air change per hour reduces the temperature variation of the room in a day and has a significant effect on the temperature maintained in the room, while the increase in the heat capacity of the helps to maintain the room temperature for longer period. The circulation of room air in the air duct helps in maintaining the higher room temperature.

# THANK YOU