Performance of PV integrated wall and roof as a building material

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Abstract. The performance of the Photovoltaic (PV) module as a building material is analyzed by predicting the hourly variation in the room temperature compared to base case (conventional material). A computer simulation model of Fourier admittance method is used for the analysis. The average temperature fluctuation of PV roof and PV wall building compared to base case is 6.58˚C and for PV wall 2.91˚C respectively. The total daily energy generation from PV wall is found in the range of 6.7 kWh to 11.86 kWh, for PV roof its 17.24 kWh to 22 kWh. Due to temperature fluctuation the max additional daily cooling load obtained in PV roof case is 94.7 kWh and 41.97 kWh for PV wall.

1. Introduction

PV technologies can be attached or integrated with the building envelopes termed as Building integrated photovoltaic (BIPV) or Building attached photovoltaic (BAPV). The BIPV technology used as a building material along with the conventional material or fully replaces the conventional one like semitransparent photovoltaic. The concept of the PV as a wall was initially given by [1]. He observed the effect of temperature on the performance of the PV modules. The author concluded that the temperature PV modules could be reduced to 15-20˚C with a ventilated duct of aspect ratio (height/depth) less than 340.

India receives abundant amount solar radiation of 5-7 kWh/m² yearly playing crucial role in growth and development of PV technologies. Due to lack of barren land and increase in future energy demand, building can be an option for installation of PV technologies like Rooftops [2]. Apart from rooftop, building envelopes can also be an option for installation of PV technologies. So the study on impact of PV as building wall and roof becomes a necessary part. Agrawal and Tiwari [3] analyze the opaque PV integrated roof using energy balance model, found moderate climate suitable in terms energy and exergy generation. Vats and Tiwari [4] developed first order energy balance model of semitransparent PV integrated with the roof to predict room temperature, they also calculated the thermal benefits in terms of exergy analysis. Taffese et al. [5] performed periodic modelling and simulation of a certain PV-TW (Photovoltaic-Trombewall) for the composite climate of New Delhi. It was found that the optimum thickness of 0.4m was suitable for maintaining thermal comfort inside the room. Tejero-González et al. [6] provides forced ventilation in PV integrated building façade for the
improvement in the thermal energy and electrical performance of PV facade. Han et al. [7] Found that opened channel behind the PV panel is an economic way of heat releasing for the benefit of PV power.

However the effect of PV module on performance of the building was not studied at large. The technology may alter/deviate the thermal comfort of the building mainly in hot summer months. In this paper we analyze effect of only PV modules as a south wall and the roof on the variation in the room temperature \( T_r \) magnitude for 24 hrs cycle. For that roof and south wall was completely replaced with the typical C-Si modules. Also the energy generation from this technology is calculated. The simulation is performed for the composite climate of New Delhi, India.

2. Analysis
For analysis a Fourier admittance method and energy balance equation as given in [8] and [9] is used for prediction the hourly temperature fluctuation in the room. The Fourier function is as given below were \( n \) is the \( n \)th harmonic

\[
f(t) = \sum_{n=\infty}^{+\infty} f_n \exp(in\omega t)
\]

The Conduction equation for heat flow through building envelopes is given as

\[
k \frac{\partial^2 T}{\partial x^2} = \rho C \frac{\partial T}{\partial t}
\]

Fourier series (Eq. 1) can be expressed with Fourier coefficients \( T_{in} \) and \( T_{on} \), respectively then the solution of Eq. 2 with suitable boundary conditions; can be written in the matrix form as

\[
\begin{bmatrix}
T_{in} \\
\tilde{q}_{in}
\end{bmatrix} =
\begin{bmatrix}
P_n & Q_n \\
R_n & S_n
\end{bmatrix}
\begin{bmatrix}
T_{on} \\
\tilde{q}_{on}
\end{bmatrix}
\]

(3)

The elements of matrix can be written as-

\[
\begin{bmatrix}
P_n & Q_n \\
R_n & S_n
\end{bmatrix} =
\begin{bmatrix}
0 & -1/h_1 \\
0 & 1
\end{bmatrix}
\begin{bmatrix}
A_{nm} & B_{nm} \\
D_{nm} & A_{nm}
\end{bmatrix}
\begin{bmatrix}
1 & -1/h_D \\
0 & 1
\end{bmatrix}
\]

P, Q, R and S depend upon the thermophysical properties of different layers mentioned in Table. 1 \( A_n \), \( B_n \) and \( D_n \) are the \( m \) layers of building envelope corresponding to the \( n \)th harmonics and given as:

\[
A_{nm} = \text{Cosh}(\alpha_n L_m), \quad D_{nm} = -K_m \text{Sinh}(\alpha_n L_m), \quad B_{nm} = -\text{Sinh}(\alpha_n L_m) / K_m, \quad \text{and} \quad \alpha_n = \sqrt{\frac{n \omega \rho_m c_m}{K_m}}
\]

\( \rho_m, c_m \), and \( K_m \), are the density, specific heat and thermal capacity of the material and \( L_m \) is the thickness of the \( m \)th layer.

The heat flux transmitted through building envelope is obtained by solving Eq (3) and can be expressed as:

\[
\tilde{q}_e = A_e \sum_{n=\infty}^{n=\infty} S_n \left( T_{in} + \frac{\alpha_n t_{an}}{h_n} \right) - \left( T_{on} + \frac{\alpha_n t_{on}}{h_n} \right) \times \exp(in\omega t)
\]

\[
+ A_e \sum_{n=\infty}^{n=\infty} (\alpha_n L_{on}) \exp(in\omega t)
\]

(4)
Where $S_n$ and $Q_n$ depend on thermo-physical properties of roof materials and $A_R$ is the area of the roof or wall. The heat gain, due to infiltration and ventilation of air from ambient into room can be given as:

\[
\dot{q}_{\text{inf}} = C_m \sum_{n=-\infty}^{+\infty} (T_{an} - T_{rn}) \times \exp(i\omega t) \tag{5}
\]

\[
\dot{q}_{\text{ven}} = C_{ven} \sum_{n=-\infty}^{+\infty} (T_{an} - T_{rn}) \times \exp(i\omega t) \tag{6}
\]

$c_{ven}$ is a time dependent term which can also be expressed in terms of Fourier coefficient as:

\[
c_{ven} = \sum_{m=-\infty}^{+\infty} c_{ven}(m) \times \exp(i\omega t) \tag{7}
\]

Heat transmission through window glass and door is expressed in terms of their respective $U$ values i.e,

\[
\dot{q}_{\text{door/window}} = A_d U \sum_{n=-\infty}^{+\infty} (T_{an} - T_{rn}) \times \exp(i\omega t) \tag{8}
\]

The room air temperature is essentially determined by the energy balance equation for the non-conditioned room can written as:

\[
M_R \frac{d}{dt} \left[ \sum_{n=-\infty}^{+\infty} T_{rn} \exp(i\omega t) \right] = \dot{q}_{\text{inf}} + \dot{q}_{\text{ven}} + \dot{q}_e + \dot{q}_{\text{door/window}} \tag{9}
\]

The response of the room temperature is also be periodic in nature and hence it Fourier analyzed from eq. (9) as, in this we have taken from harmonics $n= - 6$ to $+ 6$

\[
T_r(t) = \sum_{n=-\infty}^{+\infty} T_{rn} \exp(i\omega t) \tag{10}
\]

For generation from the PV facades and roof following expression given by [10] is used

\[
E_g = 0.12 A_{PV} I_T \left[ 1 - 0.004 \left( T_a + \frac{0.32}{0.91 + 2.0 V_f} I_T - 25 \right) \right] \tag{11}
\]

Where $A_{PV}$ is the area of PV module, $T_a$ is the ambient temperature, $I_T$ is the Total solar radiation, $\omega$ mounting coefficient value of PV technology and $V_f$ is wind speed in m/s.

## 3. Result and Discussion

A comparative study has been carried out for base case and PV case for each month (April-September), for that a non-conditioned room of dimension $(6m \times 5m \times 3m)$ is with two windows (size 1.05 m$^2$ each) facing east and west and door (size 2.0 m$^2$) assumed to be located on the east side is considered for the simulation. The calculation is performed for the composite climate of New Delhi (28.6139° N, 77.2090° E) from April to September are having the mean ambient temperature above 27.5˚ C to see the effect of PV modules on room temperature. The thermo physical properties of PV and building materials used in simulation were given in Table 1. The climatic parameter i.e. mean monthly radiation and the ambient temperature of New Delhi have shown in figure 1.
Table 1. Properties of PV and conventional layers used for the calculation [8, 11, 12]

| Cases        | Materials | Thickness (mm) | Conductivity (W/m.K) | Density (Kg/m³) | Specific Heat | Transmittivity | Absorption |
|--------------|-----------|----------------|----------------------|-----------------|---------------|----------------|------------|
| PV (Roof wall) | Glass     | 4              | 1.7                  | 2500            | 780           | 0.88           | 0.02       |
|              | EVA       | 0.8            | 0.234                | 950             | 3135          | 0.97           | 0.03       |
|              | Cell      | 0.4            | 148                  | 2330            | 710           | -              | 1          |
|              | Tedlar    | 0.05           | 0.158                | 1200            | 1090          | -              | 1          |
| Base wall    | Brick     | 230            | 0.840                | 1700            | 800           | -              |            |
|              | Plaster   | 15             | 0.72                 | 1762            | 840           | -              | 0.3        |
| Base Roof    | Brick     | 50             | 0.80                 | 1892            |               | 0.5            |            |
|              | Tile      |                |                      |                 |               |                |            |
|              | Mud Phuska| 100            | 0.520                | 1622            | 880           | -              |            |
|              | Plaster   | 12             | 0.720                | 1762            | 840           | -              |            |
|              | RCC       | 120            | 1.580                | 2288            | 886           | -              |            |

Figure 1. Climatic parameters for New Delhi

It is observed from the figure 2-7 that the temperature deviations of the PV integrated rooms were high during day time from 7:00 hrs to 18:00 hrs, after then starts decreasing due small time lag offered
by PV material. The maximum temperature reached in case of PV roof is about 44.65°C (May) and minimum of 36.65°C (August), similarly for PV wall its 41.42°C (May) and minimum 34.28°C (August). The increment in room temperature ($T_a$) in PV wall case is less than PV roof due to lower radiation fall on the vertical surface compared to roof in summer. Due to the temperature gain in PV cases, the average temperature deviations obtained from the base case temperature were used for calculating daily additional cooling loads of the building as shown in Table 2. The total daily energy generation from PV walls and roof were calculated using the Eq. (11), shown in figure 8. From fig.8, it is observed, that the maximum unit generated in PV roof case is 94.72 unit and 41.97 units for PV wall in April month. The units generated by the PV systems can cover the additional cooling load obtained in PV cases using air coolers with higher Coefficient of Performance (CoP).

![Figure 2. Hourly floating room temperature in April](image1)

![Figure 3. Hourly floating room temperature in May](image2)
Figure 4. Hourly floating room temperature in June

Figure 5. Hourly floating room temperature in July
Figure 6. Hourly floating room temperature in August

Figure 7. Hourly floating room temperature in September

Table 2. The average variation in hourly floating room temperature of PV case from Base case and additional cooling load by PV roof and wall

| Cases          | April | May  | June  | July  | August | Sep  |
|----------------|-------|------|-------|-------|--------|------|
| PV wall (ΔT)   | 2.91°C| 2.53°C| 2.10°C| 1.78°C| 1.82°C | 2.42°C|
| Additional cooling load (kWh) | 41.97 | 36.45 | 30.29 | 25.67 | 26.15 | 34.78 |
| PV roof (ΔT)   | 6.58°C| 6.41°C| 5.12°C| 4.37°C| 4.15°C | 4.93°C|
| Additional cooling load (kWh) | 94.72 | 92.32 | 73.74 | 62.88 | 59.74 | 70.93 |
4. Conclusion
The following conclusions can be drawn from the results of comparative hourly floating room temperature profiles –

- The PV modules have shown potential as a building material, with electrical benefits obtained from the PV wall and roof which can compensate the additional cooling load of the building by using electric gadgets of higher coefficient of Performance (CoP).
- It was observed that due to the small time lag mean temperature difference between the base case and PV case was around 2°C for 24 hrs of cycle.
- With the temperature deviation from base case of 2.91°C during daytime, the performance of PV wall is found better in comparison to PV roof having variation of 6.58°C; however the generation of wall is less due than roof due to low solar radiation on wall.
- An additional insulation layer can be used along with PV, which can further decrease the hourly floating temperature of the building.
- The durability and strength of the PV module as a building material can be further studied.

This analysis has been conducted for building situated in composite climate of New Delhi, but these techniques could be adapted and implemented for other climates also.
References

[1] Yang HX, Marshall RH, Brinkworth BJ 1996 Validated simulation for thermal regulation of photovoltaic wall structures Twenty Fifth IEEE Photovoltaic Specialists Conf. 1453-56
[2] Sukhatme S P 2011 Meeting India's future needs of electricity through renewable energy sources Current Sci. 624-30
[3] Agrawal B and Tiwari G N 2011 An energy and exergy analysis of building integrated photovoltaic thermal systems Energy Sources, Part A: Recovery, Utilization, and Environmental Effects 33(7) 649-64
[4] Vats K and Tiwari GN 2012 Performance evaluation of a building integrated semitransparent photovoltaic thermal system for roof and façade Energy Build. 45 211-18
[5] Taffesse F, Verma A, Singh S and Tiwari G N 2016 Periodic modeling of semi-transparent photovoltaic thermal-trombe wall (SPVT-TW) Sol. Energy 135 265-73
[6] Tejero-González A, Krawczyk D A, Martín-Sanz García J R, Rey-Martínez F J and Velasco-Gómez E 2019 Improved Performance of a PV Integrated Ventilated Façade at an Existing nZEB Energies 12(15) 3033
[7] Han J, Lu L, Yang H and Cheng Y 2019 Thermal regulation of PV façade integrated with thin-film solar cells through a naturally ventilated open air channel Energy Proced. 158 1208-14
[8] Bansal N K, Garg S N and Kothari S 1992 Effect of exterior surface colour on the thermal performance of buildings Build. Environment 27(1) 31-37
[9] Sodha M S, Singh S P and Sawhney R L 1990 Evaluation of discomfort in a room with desert cooler Int. J. of Energy Research 14(7) 745-56
[10] Skoplaki E, Boudouvis A G and Palyvos J A 2008 A simple correlation for the operating temperature of photovoltaic modules of arbitrary mounting Sol. Energy Mater. Sol. Cells 92(11) 1393-1402
[11] Hammami M, Torretti S, Grimaccia F, Grandi G 2017 Thermal and performance analysis of a photovoltaic module with an integrated energy storage system Appl. Sciences. 7(11) 1107
[12] Ruiz-Reina E, Sidrach-de-Cardona M and Piliougine M 2014 Heat Transfer and Working Temperature Field of a Photovoltaic Panel under Realistic Environmental Conditions COMSOL Conf. (Cambridge)

Nomenclature

A area, m²
\( c \) Specific heat, J/kg °C
\( h \) Convective heat transfer coefficient, W/m² °C
\( I \) Intensity of solar radiation, W/m²
\( K \) Thermal conductivity, W/m°C
\( U \) Conduction transmittance, W/m² k
\( L \) Thickness of roof slab, m
\( M_r \) Thermal Mass of room air
\( \dot{q} \) Rate of heat flow /gain
\( T_{in} \) Temperature of outer surface of roof slab, °C
\( T_{on} \)  Temperature of inner surface of roof slab, °C
\( T_{an} \)  \( n^{th} \) harmonic factor of Fourier series for ambient temperature, °C
\( T_r \)  Room air temperature, °C
\( T_{rn} \)  \( n^{th} \) harmonic factor in Fourier series for room air temperature, °C
\( t \)  time (sec)
\( \rho \)  Density of air, kg/m³
\( \omega \)  Frequency \((2\pi/time\ period)\)
\( \alpha \)  absorptivity
\( d \)  door
\( e \)  envelope (walls and roof)
\( m \)  no. of envelope layers
\( r \)  room
\( i \)  inside
\( o \)  outside
\( \text{inf} \)  infiltration
\( \text{ven} \)  ventilation