Field Study and Modeling of Semi-Transparent PV in Power, Thermal and Optical Aspects

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Abstract

In this research, semi-transparent PV is proposed as building integrated PV roof for residential application. To understand its characteristics, field measurement was carried out to examine the power generation, thermal and visible light transmission performance of poly-crystalline silicon single glass, poly-crystalline silicon double glass and amorphous silicon single glass semi-transparent PV panels in prototype scale. To confirm parameters needed in accessing semi-transparent PV panels which are seldom provided by manufacturers, calculation models were constructed and verified with field measurement data. This paper reports the findings of experimental and modeling work, which will be fundamental for evaluating semi-transparent PV in overall building energy performance in a later stage of the research. In this study, power generation temperature coefficients are obtained for each panel. For thermal characteristics, various material properties of panels are confirmed. The overall heat transfer coefficients are 4.587 W/m2K, 2.007 W/m2K and 4.379 W/m2K for p-Si single glass, p-Si double glass and a-Si single glass panel respectively. With respect to visible light transmission, semi-transparent PV possesses similar light transmission characteristics with glazing material, and thus could be modeled in the same way as normal glazing material.

Keywords: semi-transparent PV; power generation; heat balance; overall heat transfer coefficient; illuminance

Introduction

Semi-transparent PV, differing from conventional PV, are PV cells incorporated into glazing materials. Depending on the type and arrangement of PV cells, it facilitates various degrees of solar radiation and natural light penetration. Besides generating clean power, semi-transparent PV (STPV) encourages daylighting in buildings and could function as a building element. By optimizing the utilization of natural energy resources, it is anticipated to be a sustainable building material, environmentally, physiologically and economically.

Currently, STPV is gaining its niche and is widely used as PV façades in office and commercial buildings. Famous examples of STPV buildings are the Mataro Public Library in Spain (Lloret et al. 1995), and the De Kleine Aarde Boxtel in the Netherlands (Reijenga and Bottger, 1997). Buildings incorporating STPV may have the advantage of winter heating and daylighting due to direct penetration of solar radiation. However, it might suffer from summer overheating and glare problems if inappropriately designed.

To date, research of its optimization in power generation, daylighting and thermal utilization on total energy balance is relatively scarce. Current research on STPV include thermal modeling of ventilated PV façades (Infield et al. 2004; Mei et al. 2003), and simulation of total energy consumption in STPV office buildings (Miyazaki et al. 2005; Boer 2001).

In total building energy consumption, Miyazaki (2005) and Boer (2001) researched on office buildings. In this research, application of semi-transparent PV as roofing material is proposed as an alternative for the following reasons. In Japan, residential PV will be a major application in the coming decade, with annual installation estimated at 80.9% of total PV installation by 2010 (Japan Photovoltaic Energy Association). For residential installation, a roof angle of 30-35° contributes to optimum power generation in Japan with an average latitude of 35°N.

Besides, conventional rooftop PV panels cut out daylight and heat up due to scarce ventilation around the panel. Thus, here we suggest direct interaction of PV with the indoor environment. This could optimize the utilization of natural energy resources, especially daylighting and solar thermal heat during heating seasons.

As no study was carried out on the heat balance and thermal behavior of STPV panels, STPV-building total energy consumption calculations are currently done by steady state calculation, or substitution of panel temperature with glazing materials temperature. This
could not represent the actual condition, thus may lead to over or underestimation of cooling and heating load consumption and power generation due to inaccurate temperature data.

Therefore, this research aims to examine the power generation, thermal and optical behavior of STPV panels under actual outdoor conditions. With understanding and validated data from actual measurements, the effect of STPV on overall building energy consumption could be more accurately assessed.

**Research Methodology**

This study consists of field measurement and numerical simulation. Field measurement is carried out in the first stage to investigate the power generation, thermal and optical characteristics of STPV. At the same time, calculation models are constructed to predict the above behavior of STPV panels under prevailing weather conditions. These calculation models are validated against measurement data to confirm its accuracy. Finally, validated calculation models will be incorporated into a building energy simulation program to evaluate the effect of STPV on total building energy consumption.

This paper reports the findings of field investigation on the characteristics of STPV panels, and calculation models which produce calculation results that agree well with field measurement data.

**Field Measurement**

Field measurement is carried out on top of a 6-storey building in the Environmental Engineering Department of Osaka University. STPV panels are constructed on south-facing prototype huts with floor area of 1.5 m$^2$, using iron sheet, plank, insulation foam and paper as shown in Figs. 1. and 2.

![Fig.1. Field Measurement Set up](image)

Three types of semi-transparent PV panel, namely poly-crystalline silicon single glass (p-Si single), poly-crystalline silicon double glass (p-Si double) and amorphous silicon single glass (a-Si single) are investigated with a control case panel, float glass which is normally used as top lights in Japanese residential houses. Specifications of panels are given in Table 1.

![Fig.2. Configuration of Prototype Hut](image)

Table 1. Specifications of STPV Panels

|                  | Poly-Crystalline Silicon Single Glass | Poly-Crystalline Silicon Double Glass | Amorphous Silicon Single Glass |
|------------------|--------------------------------------|--------------------------------------|--------------------------------|
| Panel size [m$^2$] | 0.7744                               | 0.7744                               | 0.9408                         |
| Open circuit voltage, $V_{oc}$ [V] | 12.03                                | 12.06                                | 91.8                            |
| Short circuit current, $I_{sc}$ [I]  | 7.842                                | 7.86                                 | 0.972                           |
| Optimum voltage, $V_{pm}$ [V]        | 9.235                                | 9.24                                 | 59.6                            |
| Optimum current, $I_{pm}$ [I]        | 6.939                                | 6.982                                | 0.638                           |
| Visible light transmission [-]       | 0.42                                 | 0.42                                 | 0.1                             |

Measurements are recorded every minute throughout the year (ETO 200 Thermduc E200 data logger). Measured data include horizontal and 30° in-plane global radiation (EKO MS-802 Pyranometer); horizontal short wave radiation in each hut (EKO MS-601 Pyranometer); outdoor drybulb, panel front and rear surface, hut indoor temperature (K - Thermocouple 0.1mm²); horizontal global, sky, indoor illuminance (EKO ML-020 illuminance meter); wind speed and wind direction (Young 03002V Wind Sentry); outdoor and hut indoor atmospheric radiation (EKO MF-11 atmospheric radiation meter); and PV power generation.

Each PV panel is connected to a maximum power point tracker (MPPT) for optimum power generation under various insolation conditions. The current and voltage of PV panels are measured in the circuit shown in Fig. 3.
Calculation model

1. Power generation model

The power generation model uses input data of 30° in-plane insolation to calculate the output power, \( P \) of STPV panels with the following equation (NEDO 2000, Imagawa et al. 2002).

\[
P = P_{\text{AS}} \cdot H_a \cdot K_{\text{pt}} \cdot K_w \cdot K_c \cdot K_e
\]

\( P_{\text{AS}} \): Power generation under standard test conditions [W]
\( H_a \): Incident solar radiation [W/m²]
\( K_{\text{pt}} \): Coefficient due to cell temperature rise [-]
\( \alpha \): Temperature coefficient [-]
\( K_w \): Compensation for installation criteria [-]
\( K_e \): Coefficient related to blocking diode, wiring, dirt [-]
\( K_c \): Compensation for loss during power conversion = 0.945

2. Thermal balance model

PV panels are divided into horizontal sections shown in Fig.4.

Equations below show heat balance of single glass panel.

Front surface (layer 1) heat balance:

\[
\varepsilon_{\text{f}} \cdot J \cdot \frac{1 + \cos A}{2} - \varepsilon_{\text{f}} \cdot \sigma (T_1 + 273 \cdot 15) + \alpha \cdot (T_0 - T_1) - \frac{(T_1 - T_2)}{R_1} = 0
\]

Outer glass (layer 2) heat balance:

\[
CR_{\text{gs}} \cdot L_g \left( \frac{T_2 - T_2^{\text{prev}}}{dt} \right) + \frac{(T_2 - T_3)}{R_1} + \frac{(T_4 - T_3)}{R_2} - B_2(I_o + I_a) = 0
\]

Cell and EVA (layer 3) heat balance:

\[
CR_{\text{pg}} \cdot L_g \left( \frac{T_3 - T_3^{\text{prev}}}{dt} \right) + \frac{(T_3 - T_4)}{R_3} + B_3(I_o + I_a) + P = 0
\]

Inner glass (layer 4) heat balance:

\[
CR_{\text{gs}} \cdot L_g \left( \frac{T_4 - T_4^{\text{prev}}}{dt} \right) + \frac{(T_4 - T_5)}{R_3} + \frac{(T_5 - T_4)}{R_4} = 0
\]

Rear surface (layer 5) heat balance:

\[
\alpha_{\text{R}} (T_5 - T_5) + \alpha_{\text{R}} (T_5 - T_5) + \frac{(T_5 - T_5)}{R_4} = 0
\]

In the heat balance equations above, parameters affecting panel heat balance are examined. These parameters include radiation absorption factor and thermal characteristics, which are not fully provided by manufacturers. Currently, power generation uses actual measurement value. In the future, the power generation calculation model (Equation (1)) will be incorporated.
into Equation (4) for higher accuracy in heat balance calculation.

With available data from manufacturers, reference sources and field measurement, these parameters will be validated to represent the overall heat balance of a semi-transparent PV panel.

3. Direct illuminance model

Direct illuminance inside each prototype hut are calculated as shown in Fig. 5. (Architectural Institute of Japan).

Results and discussions

1. Power generation

As is well understood, PV power generation deteriorates when cell temperature increases. Thus, for accurate prediction of STPV power generation, we examined the temperature coefficients (a in Equation (1)) of each panel through actual measurement.

For single glass panels, rear surface temperature of the panel is taken as the cell temperature. As the rear surface temperature does not fluctuate as much as the front surface temperature, temperature gradient between rear surface and PV cell is smaller, thus it could better represent the cell temperature. However, in the case of the double glass panel, due to the insulation air layer between the cell and the inner glass layer, the actual cell temperature may differ somewhat with the rear surface temperature. Thus, for double glass panel, front surface temperature is taken as the cell temperature. The slope of best-fitted line in Figs. 6. through 8. represents the temperature coefficients of each STPV panel.

Temperature coefficients obtained are –0.59%/°C for p-Si single glass, –0.65%/°C for p-Si double
With the obtained temperature coefficients, power generation is modeled and compared with measured data. Figs. 9. through 11. show comparison of measured and calculated power generation for each panel.

As shown, the obtained temperature coefficient could represent the actual STPV power generation. Thus, it could be concluded that the obtained STPV temperature coefficient, which is –0.59%/°C for p-Si single glass, -0.65%/°C for p-Si double glass and –0.16%/°C for a-Si single glass can be used to estimate STPV power generation with adequate accuracy. As Figs. 9. through 11. show good agreement between calculated and measured power generation, the values of $K_c$, $K_o$ and $K_i$ used in calculation are considered valid.

2. Panel heat balance

Panel temperature affects power generation, radiative and convective heat transfer from panel into building. Thus, accurate prediction of panel temperature assures precise calculation of building heating and cooling load as well as power generation.

Heat balance of each STPV is calculated with equations in the previous section. Tables 2. and 3. show the material and optical parameters of each STPV panel used in the heat balance calculation model.

| Material Properties of STPV Material | Heat conductance | Density | Heat capacity |
|-------------------------------------|------------------|---------|---------------|
| Glass 5mm                           | 0.78             | 3000    | 500           |
| Wired glass 6.8mm                   | 0.9              | 3000    | 500           |
| EVA                                 | 0.116            | 2330    | -             |
| Silicon cell                        | 168              | -       | 677           |

| Optical Properties of STPV Material |
|-------------------------------------|
| Absorptance | Transmittance | Reflectance |
| Glass 5mm   | 0.112         | 0.815       | 0.073        |
| Wired glass 6.8mm | 0.193    | 0.734       | 0.073        |
| EVA         | 0.060         | 0.900       | 0.040        |
| Silicon cell | 0.970       | -           | 0.030        |

Heat conductance and heat capacity in Table 2. are quoted from Yoshimura et al. (2002) and Li Mei et al. (2003) respectively, while optical properties in Table 3. needed for the calculation of radiation absorption factors are obtained from manufacturer’s catalogue. For front surface convective heat transfer coefficient, constant values were examined using sensitivity analysis, by comparing calculated and measured front surface panel temperatures. Results of sensitivity analysis indicate that value of 15 W/m²K for p-Si panels and 10 W/m²K for a-Si panel could represent the surface convective heat transfer of the panels. The difference in value is due to different wind fields at the roof top.

For rear surface heat transfer, as air velocity behind the panel is low, only natural convective heat transfer is assumed (Equation (7), Jones et al. (2001)).

$$\alpha_i = 1.31 \cdot \left| T_3 - T_d \right|^{1/3} \quad (7)$$
Radiative heat transfer coefficient uses the value of 4.5 W/m²K (SHASE 1995).

Fig. 12 shows measured and calculated front and rear temperatures of each panel. As illustrated, calculated temperatures agree well with measured temperatures. Thus it could be concluded that the properties of materials used in calculation, as well as the various heat transfer coefficients could effectively represent the actual STPV under field measurement conditions.

With the verified material properties and heat transfer coefficients, thermal performance of each STPV panel are examined through the overall heat transfer coefficient parameter given in Equation (8).

\[
K = \frac{1}{\frac{1}{\alpha_o} + \sum \frac{l_j}{\lambda_j} + \frac{1}{(\alpha_f + \alpha_r)}}
\]  

(8)

\(K\): Overall heat transfer coefficient [W/m²K]  
\(l_j\): Thickness of layer-j [m]  
\(\lambda_j\): Thermal conductance of layer-j [W/mK]  
\(\alpha_f\): Panel front surface convective heat transfer coeff. [W/m²K]  
\(\alpha_r\): Panel rear surface convective heat transfer coeff. [W/m²K]  
\(\alpha_r\): Panel rear surface radiative heat transfer coeff. [W/m²K]

In Equation (8), for comparison purpose, the front surface convective heat transfer coefficients use the value of 15 W/m²K for all panels. Rear surface convective heat transfer coefficients, obtained from Equation (7) are given the value of 3 W/m²K, which is the average of all panels under different weather conditions. Radiative heat transfer coefficient uses the value of 4.5 W/m²K (SHASE 1995).

For poly-crystalline silicon panels, PV cells do not spread all over the panel as in amorphous crystalline silicon panel (Fig.13). Thus, the overall heat transfer coefficient of panel should consider both portions with and without PV cell.
Below (SHASE 1995).

Equivalent thermal resistance ($R_{eq}$) of the center layer which contains both PV cell and glass could be represented in Fig. 14. For portion without PV cell, glass with the same thickness as the total of cell and EVA is assumed.

\[
K = \frac{1}{R_o + R_{eq} + \sum R_j + R_{in}} \quad (9)
\]

$K$: Overall heat transfer coefficient [W/m²K]

$R_o$: Front surface convective thermal resistance [m²K/W]

$R_{eq}$: Equivalent thermal resistance of cell and glass [m²K/W]

$R_j$: Thermal resistance of layer-$j$ [m²K/W]

$R_{in}$: Rear surface convective and radiative thermal resistance [m²K/W]

Applying formula for parallel resistance in a circuit, the area-weighted equivalent thermal resistance can be obtained with Equation (10):

\[
\frac{1}{R_{eq}} = \frac{Cell Area}{R_{cell+EVA}} + \frac{Glass Area}{R_{glass}} \quad (10)
\]

The calculated overall heat transfer coefficient of each STPV panel are tabulated in Table 4.

Table 4. Overall Heat Transfer Coefficient of STPV Panels

| Panel                                | $K$ [W/m²K] |
|--------------------------------------|-------------|
| Poly-crystalline silicon single glass| 4.587       |
| Poly-crystalline silicon double glass| 2.007       |
| Amorphous silicon single glass       | 4.379       |
| 6 mm float glass                     | 4.815       |

Calculation results show that single glass STPV panels possess better thermal resistance compared with float glass. This is due to the occurrence of PV cell layer which increases the overall thermal resistance of the panel.

Between single glass panels, poly-crystalline silicon panel exhibits a slightly higher heat transfer coefficient. As shown in the resistance network calculation, total resistance of the layer of panel with and without cell actually decreases due to its parallel connections.

In the case of the double glass panel, as anticipated, sufficient insulation character is proved by its relatively low heat transfer coefficient, which is about half of the single glass panel values.

Thus it could be concluded that STPV could perform equally well as glazing materials with the relatively similar heat transfer coefficient. However, it should be noted that $K$ value only applies under natural temperature gradient condition between panel surfaces, without considering heat loss or heat gain contributed by solar heat absorption and power generation of the PV cell. To effectively evaluate STPV, a dynamic heat balance evaluation is necessary.

3. Visible light transmission

The difference between conventional PV and STPV is the ability of visible light transmission through STPV panels. For optimum utilization of daylighting, visible light transmission plays an important role.

In this respect, visible light transmission through STPV panel is examined through illuminance measurement, for the purpose of daylighting evaluation.

The reference point for illuminance measurement is 21 cm below the center point of each panel. This position enables the measurement of only direct illuminance through the panels, eliminating uncertainties brought by reflected illuminance in calculating visible light transmission.

Measured and simulated values of illuminance at a reference point inside each hut is compared to confirm the visible light transmission rate of different panels. As poly-crystalline silicon panels have a similar cell arrangement, the visible light transmission data of only one representative panel is shown.

Comparisons of measured and calculated illuminance are depicted in Figs. 15 and 16.

The resulting graphs show that STPV panels have similar visible light transmission behavior as usual glazing material, which could be represented as percentage transmission and modeled in the same way as usual glazing material.

For poly-crystalline silicon STPV panels, visible light transmission could be modeled as the percentage area of clear glass in the total panel area. The high illuminance level during noon and low illuminance level during the rest of the day is due to the location of measurement point, which is at the middle of the panel, directly under the glass portion. During noon period, visible light penetrates almost directly through the glass; while during rest of the day, most of the visible
light is blocked by the poly-crystalline cells on both sides of the measurement point.

In the case of the amorphous-crystalline silicon panel, the value of visible light transmission given in panel specification adequately represented the actual visible light transmission behavior of the panel.

Conclusions
To examine the power generation, thermal and optical behavior of STPV panels under actual outdoor conditions, field measurement and numerical modeling was carried out.

Power generation temperature coefficient of STPV is obtained as -0.59%/°C for poly-crystalline silicon single glass, -0.65%/°C for poly-crystalline silicon double glass and -0.16%/°C for amorphous silicon single glass panel.

Heat balance of each panel is examined and is represented relatively well by our calculation model. The overall heat transfer coefficient, $K$, which is usually a thermal performance evaluation parameter, is also obtained. Poly-crystalline silicon double glass panel shows the highest insulation performance, with an overall heat transfer coefficient of 2.007 W/m²K. Both single glass panels shows relatively low overall heat transfer coefficient, which is 4.379 W/m²K for amorphous silicon panel and 4.587 W/m²K for poly-crystalline panel compared with float glass. Although both single glass panels have the similar layer construction, thermal performance of poly-crystalline panel tend to decrease due to its uneven cell location.

Visible light transmission for the poly-crystalline silicon STPV is determined by the configuration of cell and glass in the panel.

To conclude, the power generation, thermal and visible light transmission behavior of STPV is examined and understood. Findings and data will be used to further evaluate STPV in the overall building energy simulation process.

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