

Article

Experimental Study on the Thermal, Electrical, and Visual Performance of a Transparent Vacuum Insulation Panel with Attached Film-Based Semi-Transparent Photovoltaic Panel [†]

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[†] This paper is an extended version of a conference paper presented in CPESE 2024—The 11th International Conference on Power and Energy Systems Engineering, Nara City, Japan, 6–8 September 2024.

Abstract

This proof-of-concept study proposes a photovoltaic transparent vacuum insulation panel (PV-TVIP) and evaluates its heat transfer and power generation characteristics with increased temperatures, and light transmission characteristics for visible light and ultraviolet wavelengths. The study was conducted with a climate-controlled chamber mimicking the common temperature range of Sapporo, Japan. The average TVIP heat flux was measured to be 65–75 W/m² with a U-value of 1.95–2.3 W/(m²·K). Compared to earlier measurements to see the effect of seasonal atmospheric conditions to the quality of the TVIP, it was determined that the TVIP manufactured during winter conducted less heat, assumed to be caused by decreased humidity. Placing the PV between the TVIP and a glass pane increased the operating temperature by 26.06 °C and decreased power generation by 13%. Afterwards, the transparency of the TVIP and PV-TVIP were measured under a bright light therapy lamp, showing that TVIP reduced the amount of most visible light wavelengths by 50% and the PV-TVIP by 90%. UV radiation was respectively reduced by approximately 78% and 100%. The results show that while PV-TVIP shows potential as a BAPV window retrofit solution, its manufacturing requires optimized, low-humidity conditions during all phases of the manufacturing process.

Keywords: transparent vacuum insulation panel (TVIP); window insulation; thermal insulation retrofit; building-attached photovoltaic;

Academic Editor: Gerardo Maria Mauro

Received: 10 May 2026

Revised: 8 June 2026

Accepted: 3 July 2026

Published: 6 July 2026

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1. Introduction

As a side effect of humanity's technological progress, a vast part of the population in developed countries now spend a substantial part of their time inside buildings, be it for business or pleasure reasons [1–3]. The human mind, however, evolved under the vast open skies, the effects of which we can see within ourselves in the forms of mood swings and issues with mental health if sufficient natural light is not experienced for an extended period [4]. A great natural example of this can be seen with the effects of seasonal affective disorder experienced by people living in the polar regions of the world. For this reason, large windows are often chosen for residential houses. This, however, is a balancing act

between living comfort and energy efficiency, as windows are one of the main contributors towards heat loss in buildings [5]. While increasing the insulation performance of windows is one of the main ways to improve their energy efficiency, another way to do this is by incorporating photovoltaic (PV) components into the construction itself in the form of building-integrated or building-attached photovoltaics (BIPV and BAPV, respectively), where the former replaces parts of traditional building envelope with PV materials in a permanent manner and the latter has PV systems attached to the envelope without replacing the envelope materials [6]. These PV systems can be incorporated to horizontal, angled, and vertical planes [7] that would otherwise be either unused or underutilized, which would then contribute to producing usable energy closer to the places where it is needed, as well as offering shade and potential added heating, lowering the overall amount of energy that would otherwise need to be produced via more polluting means [8].

One of the issues with wall-mounted PV systems is the suboptimal angle of the vertical panels, an issue that becomes more pronounced the closer the system's location is to the equator. Cronemberger et al. [9] noted that the usual practice of extrapolating guidelines made from data collected in northern countries such as Germany, Japan, and Spain may not produce accurate data in equatorial regions. They calculated that while the difference in solar incidence angle does decrease energy production potential of wall-mounted systems by more than 40% when compared to roof-mounted systems, the increased amount of irradiation experienced in Brazil (region between 0° S and 30° S latitudes) can still make these systems viable. Another study conducted by Oh & Park [10] showed that while the total roof and façade area of the Gwanak campus of Seoul National University was roughly the same, the generation potential of the facades was roughly 40% lower than the roofs. However, they also noted that the facades are rarely used for anything and thus will likely have more usable space available for BIPV installations than the roofs would. Further, Huang & Zhao [11] noted that direct solar irradiance may still cause thermal discomfort even during colder months of the year. Adding any form of shade to the windows will help with this, which would then return the conversation to finding a balance between the need for natural sunlight, the added heating that should be welcome to decrease the heating loads inherent during winters, and the excess heat caused by solar irradiance. While their study was conducted with simulations of several glazed openings with different sizes and positions on a wall, this could still be used as a basis on evaluating how BIPV/BAPV modules would affect the mentioned values.

When it comes to the placement of window BIPV/BAPV modules, three positions can be considered: completely on the outside of the window [12], built within the window [12], or on the indoor side of the window. Positioning the modules on the outside has the benefits of being able to place the panels at a more optimal angle for power generation, as well as being able to set the panels slightly away from the window on separate mountings. Placing the PV-modules directly inside the windows during the construction phase is an option that has come available with the advent of thin semi-transparent PV solutions. Yao et al. [13] studied the heating effect of PV cells mounted inside large windows with both simulated and experimental tests. They concluded that while the PV cells did increase the indoor surface temperature of the glass walls, this was largely offset by the amount of cooling provided by the shading effect of the panels. The efficiency of the panels themselves suffered slightly due to the increased temperature caused by lack of ways to cool the panels; this heating effect essentially vanished during cloudy periods. Lu & Law [14] created a simulation on a similar situation, which showed that adding a semi-transparent PV element to a window decreased the heat gain of a simulated room by 65%. They also pointed out that the solar panels produced the best results when pointing towards south-east instead of directly towards south, as strong solar irradiance causes the south-facing

panels to heat up unnecessarily, increasing the heat load of the simulated room without additional benefit in power generation. On the other hand, Knera et al. [15] showed that during winter months in the northern hemisphere it was possible for south-facing BIPVs to completely offset the lighting requirements during the whole winter, with eastern and western orientations being capable of same outside of the darkest period between November and February.

López & Sangiorgi [16] studied the balance between the shading provided and additional generated heat caused by different glass/glass insulated BIPV modules against solar radiation during winter and how these would affect the heating and lighting loads of the experimental spaces; they noted that the type and efficiency of the used PV panels greatly determine the resulting values for heating and lighting loads. In the same vein, Roeleveld et al. [17] conducted a numerical and experimental study on the cooling effect of air flow between the PV and insulation layers in a BIPV/Thermal system, showing that the surface temperature of the PV increased sharply when changing between strong and moderate mass flow rates.

Balancing all the requirements of thermal and visual comfort, energy efficiency, climate actions, etc., is something that has been studied extensively for decades [18,19]. The authors' research group has conducted research on vacuum-based window insulation retrofit options, namely with the concept of a transparent vacuum insulation panels (TVIPs), which would offer a lightweight, easy to install, and cheap retrofit solution for window insulation retrofitting, with the goal of addressing the issues with insufficient window insulation without requiring major renovations. In the first of these studies [20], it was shown that a TVIP can attain equivalent or better center-of-panel insulation performance than traditional vacuum glazing when the glazing area is smaller than 30 by 30 cm and the internal vacuum pressure is between 0.1 and 1 Pa, and additional better thermal resistance over the total area of the samples when the internal pressure is increased to 10 Pa. In the second study [21], it was shown both numerically and experimentally that TVIPs with peak-, mesh-, and frame-type cores could reach center-of-panel thermal conductivity values close to 0.006 W/(m·K). Finally, a third study was conducted regarding the addition of several combinations of regular glazing, semi-transparent PV glazing, vacuum glazing, and TVIP [22], showing the effect of increased temperature to the performance of the PV panel. From this baseline, the effects of adding a film-based semi-transparent photovoltaic panel to the TVIP became of interest as the TVIP could act as a base plate for the PV panels, effectively creating a BAPV solution; this configuration was named PV-TVIP. The experiments in [22] were conducted with glass-based PV panels, from which this study expands by measuring the effects of installing a film-based PV directly to the TVIP instead, reducing the weight and thickness of the construct.

However, with the addition of a PV panel, a question arises regarding lowered transparency, as the value of having windows in a building comes from the inhabitants being able to see to the outside as much as from having natural light entering the building. In polar regions of the world, extended periods of darkness are experienced during winters due to the angle of the Earth's axis pointing away from the sun. This lack of natural sunlight often causes decreased moods in people living in these regions, which can in worse case scenarios manifest in seasonal affective disorder (SAD) or even bouts of clinical depression [23]. To combat this, bright light therapy with lamps simulating natural sunlight have been found to be an effective tool in both prevention of SAD symptom onset as well as treating them once present [24]. From this basis, the present study also introduces initial measurements on the decrease in intensity that visible light and ultraviolet radiation experience when passing through both a regular TVIP and a PV-TVIP.

In summary, earlier studies into TVIP have mostly focused on the thermal performance of the panel and the use of glass-based PV panels. This study will add to the liter-

ature by acting as proof of concept for the possibility of using the TVIP as a BAPV solution with a film-based PV panel, and what effect this would have on the opaqueness of the fenestration system of a building. This study is an extension of a conference paper the authors presented at the 11th International Conference on Power and Energy Systems Engineering (CPESE) 2024 [25]; the results from measurements conducted in 2025 and the transparency analysis results have not been published before in any format.

2. Materials and Methods

2.1. PV-TVIP

2.1.1. Experimental Setup

The proposed TVIP is composed of 3D-printed acrylonitrile–butadiene–styrene (ABS) plastic core samples that are heat-sealed under vacuum conditions into a composite plastic envelope consisting of polyethylene terephthalate (PET), polyamide (PA), and cast polypropylene (CPP) layers. A sheet of low-emissivity film ($\epsilon = 0.1$ in this study), getter agent tablets, and potential support structures such as sheets of PET like in the current study are also enclosed inside as countermeasures for thermal radiation, internal pressure increase, and panel deformation under pressure, respectively (Figures 1 and 2).

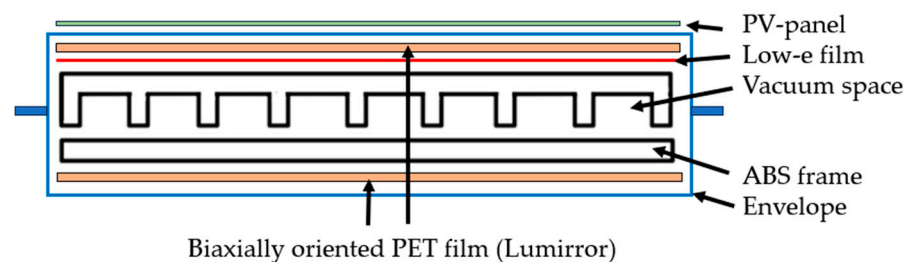


Figure 1. PV-TVIP internal components and their relative locations.

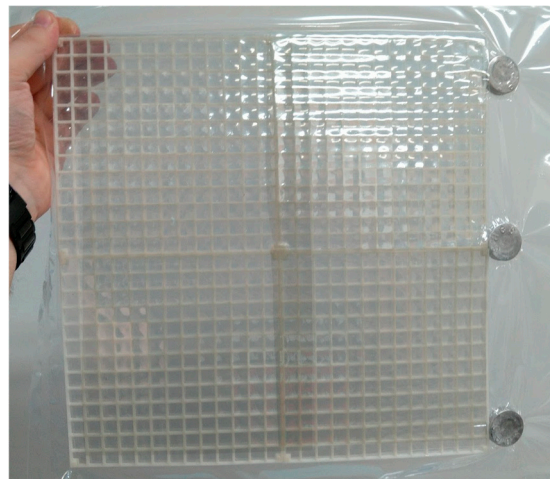


Figure 2. Sealed TVIP sample used in the measurements of this study.

Four cores were used for the TVIP due to the size of the PV panel procured for this study, with three getter agent tablets chosen to be used for the same reason. This study used the same printed cores that were used in [25,26]. The core dimensions of the samples were identical to each other, with the dimensions of one quadrant listed in Table 1. The sample cores were kept vacuum-sealed inside a TVIP during the period between the experiments to reduce the degree of deterioration of the ABS components that would occur if stored under regular atmospheric conditions. The TVIP vacuum sealing process consisted of a 24 h cycle of drying the cores in a vacuum oven set to 60 °C, followed by addi-

tional 2 h under vacuum conditions inside the heat-sealing machine prior to sealing the envelope. This preparatory phase was first conducted in 2024 and repeated before the 2025 measurements to ensure the same baseline pressure inside the envelope caused by core outgassing and gas intrusion through the outer envelope during the storing period. The PV panel used in this study was a professionally created model [27], with its specifications itemized in Table 2. The physical experiments were set up in a manner similar to those conducted by Radwan et al. [22]. An indent was cut halfway through a large block of polystyrene foam (original thickness = 5 cm), with a 30 by 30 cm area in the center of the indent being cut completely through. The TVIP and PV-TVIP samples were placed into the indent, and the block was placed into the doorway of the same climate-controlled chamber (Sanyo Incubator, model MIR-253, Sanyo Electric Co., Ltd., Osaka, Japan) used in the study by Radwan et al. [22] (Figure 3).

Table 1. TVIP structural core dimensions [25].

Dimension	Value [mm]
Total width	151.6
Span between pillars	10
Lattice width	1.6
Pillar length	1.3
Lattice thickness	1.15
Total panel thickness	4

Table 2. PV panel specifications as received from the manufacturer [27].

Type	Organic Thin Film Solar Cells
Module width [mm]	343
Module length [mm]	370
Open-circuit voltage (V_{oc}) [V]	15.7
Short-circuit current [A]	0.29
Maximum output power [W]	2.1
Number of solar cells connected in series	20

Two separate experiments were conducted in March 2024 and May 2025, both conducted with the same data logger (Yokogawa GP20-1J1M, Yokogawa Electric Corporation, Tokyo, Japan). The placement of the heat flux and thermocouple sensors during the 2024 measurements can be seen in Figure 4; the heat flux sensors were placed close to the getter agent tablets to get their full adsorption benefits. Thermocouple sensors 1–3 were placed on the side of the panel facing the chamber, while sensors 5–7 were on the side facing the laboratory. Thermocouple sensors 4 and 8 were attached to the polystyrene foam to monitor air temperature, sensor 9 measured the laboratory ambient temperature approximately 1 m away from the chamber. The measurements in 2025 used 9 temperature sensors per surface (Figure 5) to receive a more accurate measure of the average temperature across the PV-TVIP surfaces. The 2025 measurements also included the addition of a 2 mm thick glass pane ($\lambda = 0.85 \text{ W/m}\cdot\text{K}$) attached to the side of the PV-TVIP facing the halogen lamp, mimicking a situation where the PV-TVIP would be situated when installed on a window. The TVIP was recreated for the 2025 measurements in the previously described manner, replacing the 24 h vacuum oven cycle with using a newly installed heating element inside the vacuum sealing machine set to 60 °C during the sealing process. This manner of manufacturing ensures that the ABS cores do not absorb any excess moisture during the time it takes to transfer the materials between the vacuum oven and the vacuum sealing machine.



Figure 3. March 2024 physical measurement setup.

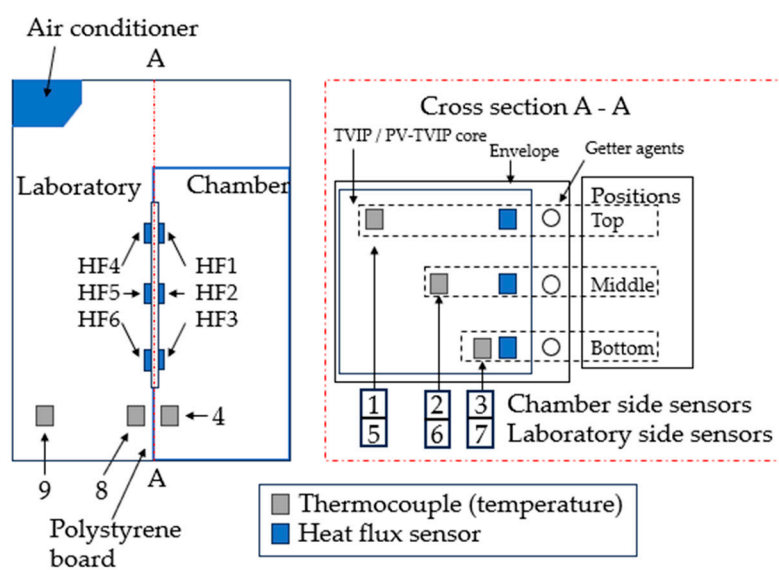


Figure 4. March 2024 measurement setup, sensor placement. The dotted red A-A line in the side-view on the figure's left corresponds to the frontal cross-section image on the figure's right.

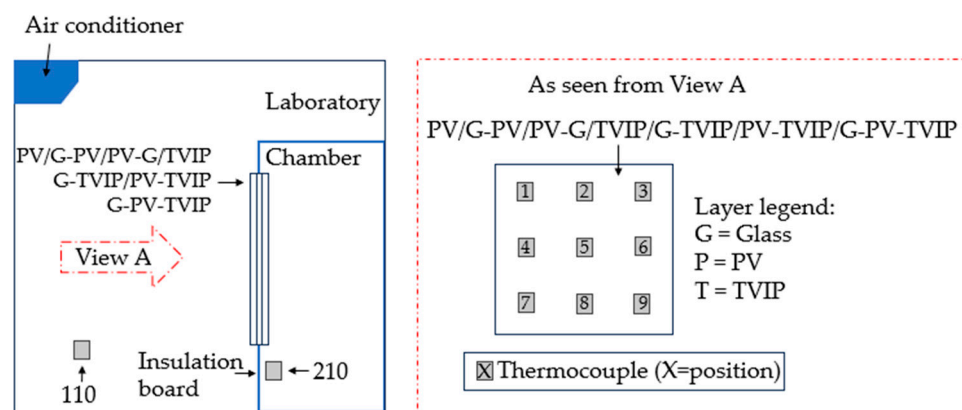


Figure 5. May 2025 measurement setup, sensor placement. Side view of the setup on the left, frontal cross-section view on the right. Numbers correspond to sensor positions used for data handling.

In the 2025 measurements, five combinations of the PV panel, TVIP, and the glass pane were measured, as shown in Figure 6. The order of the identifiers explains the order of the components as seen from View A. As an example: sample G-PV has the glass pane as the outer layer facing the lamp and the PV panel inside the chamber, while PV-G has the PV panel as the outer layer. The PV panel was attached to the TVIP face from each corner with double-sided tape ($A = 3 \text{ cm} \times 3 \text{ cm}$), with an additional attachment point placed in the middle of the panel. In the case of the G-PV and PV-G experiments, the PV panel was attached directly to the glass pane face with the same five attachment points. The TVIP and PV-TVIP were further attached to the glass pane from the center of all four sides with regular see-through tape. The layers in Figure 6 are shown separate from each other for illustrative purposes; the components were directly attached to each other during the measurements. Sensors with thin cross-sectional profile were used to measure values between the PV panel and the glass pane to keep the produced gap as small as possible. The full physical measurement setup is shown in Figure 7. These measurements were conducted until a steady state had been achieved and kept relatively constant for at least 30 min. For the PV-TVIP measurements, the voltage and current of the PV panel were also measured under a 250Ω load to see how these values would change from increased panel temperatures.

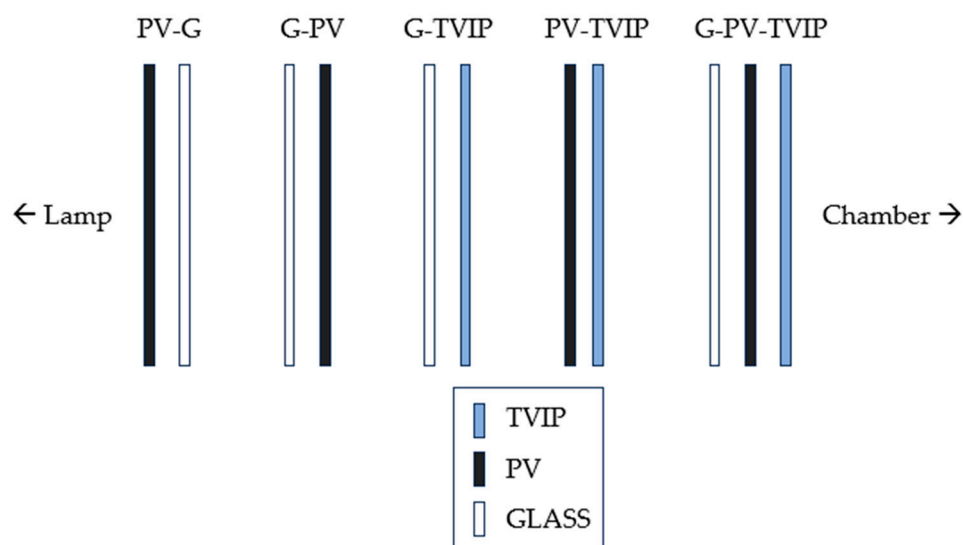


Figure 6. May 2025 sample compositions and their orientation relative to the chamber.



Figure 7. May 2025 physical measurement setup.

2.1.2. Experimental Conditions

The experimental conditions for the PV-TVIP measurements are shown in Figure 8, with the temperature values chosen to simulate summer and winter conditions in Sapporo, Japan [28]. A halogen lamp was placed in front of the samples at a distance that produced a measured radiation of 1000 W/m^2 to simulate sunlight during the summer condition experiments (Figure 8A,B). While the spectrum of the lamp does not match that of solar radiation, it was deemed as a reasonable replacement in this case as the objective of this first section was to measure the effects of radiation at a specific intensity instead of at specific wavelengths; measurements on PV-TVIP transparency were conducted in the transparency analysis section of this study. The chamber temperature was set to 25°C and -10°C , respectively, for the summer and winter conditions, laboratory temperature was kept at 23°C with an air conditioning unit. While these temperature values are slightly larger than the long-term average annual high and low temperatures in Sapporo [28], the difference was deemed acceptable in the light of the current state of climate change. The summer condition measurements were conducted first in the previous study [26], raising doubts on whether the heating of the core material could have caused additional outgassing, which would have affected results. To measure this effect, the 2025 PV-TVIP measurements were conducted twice with the TVIP recreated between the measurements to see whether the order of the experiments influenced the results. Measurements were also conducted with the halogen lamp raised and then tilted downwards at a 45° angle while keeping the distance between the center of the panel and the center of the lamp the same as with the A-B setups in Figure 8. This was done to roughly simulate the effect that natural sunlight would have during the intended use case of the TVIP: being attached to a window. The measurements for the summer and winter conditions were named Hot and Cold, respectively; the heated experiments were further labelled as center (Hot_C) and

above (Hot_A) based on the position of the halogen lamp. An additional measurement was later added to the 2025 measurements out of pure curiosity, where one of the heat flux sensors was removed from inside the chamber and placed between the PV and TVIP panels. This experiment was named “hot, between” (Hot_BTW).

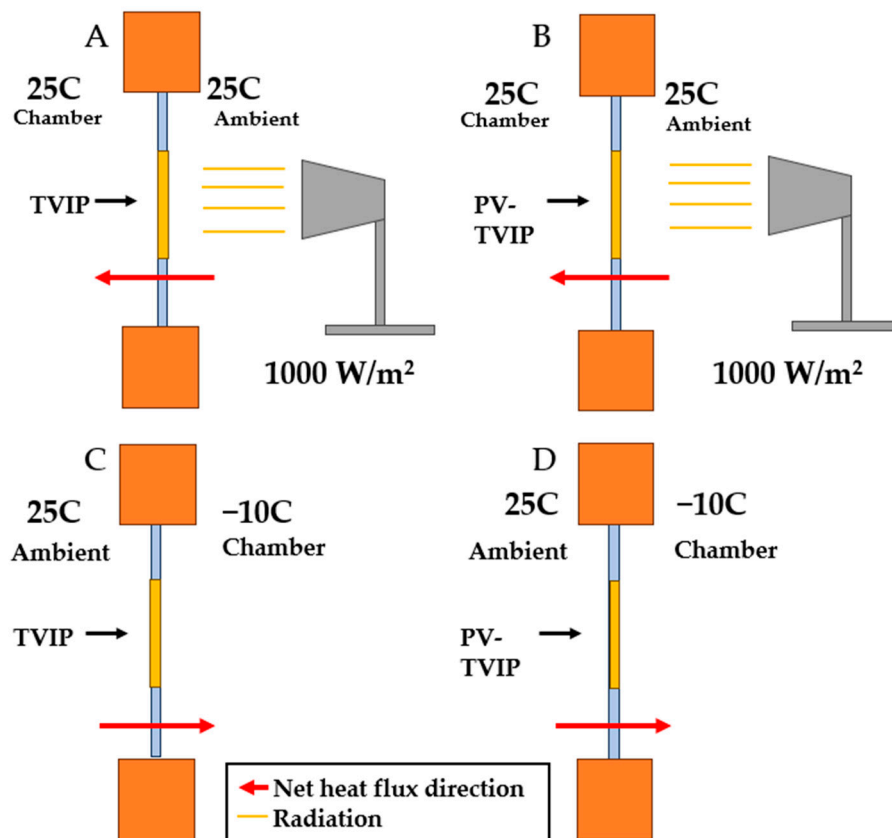


Figure 8. PV-TVIP experimental conditions: (A) TVIP Hot_C; (B) PV-TVIP Hot_C; (C) TVIP_Cold; (D) PV-TVIP_Cold.

2.2. Transparency Analysis

The physical measurement setup for measuring the TVIP transparency is shown in Figure 9. The spectroradiometer used in this study was made by Soma optics, Ltd. (Tokyo, Japan), model HIDAMARI mini S-2440C, the error margins of which are collected in Table 3. Gathered data was recorded with the manufacturer’s data handling software SpectIRR, Ver.6.2.2. The irradiance sensor was inset between 5 cm tall polystyrene blocks to protect the data cable; all other laboratory lights were turned off during measurements. The height of the lamp from the irradiance sensor was not specifically defined prior to measurements as the purpose was to see the relative decrease in the values, the total distance between the measuring device and the light source ended up being 22 cm where the items being measured were 17 cm from the light source and 5 cm from the sensor. At this distance, the measured illuminance of the lamp was approximately 50,000 lx.

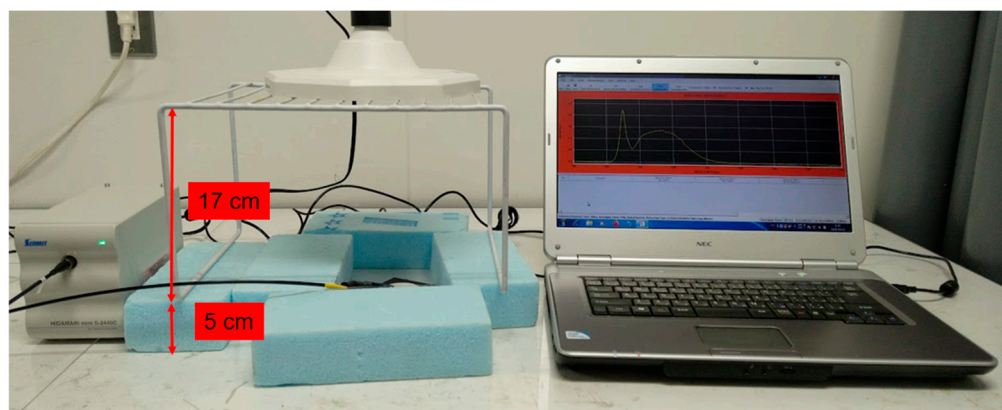


Figure 9. Transparency measurement physical setup.

Table 3. Spectroradiometer error margins.

Measured Value	Error Margin
Wavelength precision [nm]	± 0.25
Spectral bandwidth [nm]	± 6.0
Linearity [%]	± 5
Irradiance calibration [counts/ $\mu\text{W}/\text{cm}^2/\text{nm}$]	1.5
Variation between calibrated and measured values [$\mu\text{W}/\text{cm}^2$]	± 0.3
Measured value variation [$\mu\text{W}/\text{cm}^2$]	± 0.1
Sensor RMS	5 ms exposure: <150 1000 ms exposure: <200

The unscaled spectrum of the bright light therapy lamp procured for this study as well as that of the Sun [29] are shown in Figure 10, the spectrum of the therapy lamp was measured with the same spectroradiometer as was used in [21]. While the procured lamp is an LED one and thus does not produce infrared waves in the range of 780 nm to 1 mm and above in the same manner as the sun would, the authors believe this to not be an issue as the effect of TVIP to infrared radiation should be directly proportional to the level of low-e film being used. Further, the difference in waveform should not be an issue in the scope of this study, as the purpose of the study is to measure the relative decrease in intensity. This lamp will further be referred to as a therapy lamp.

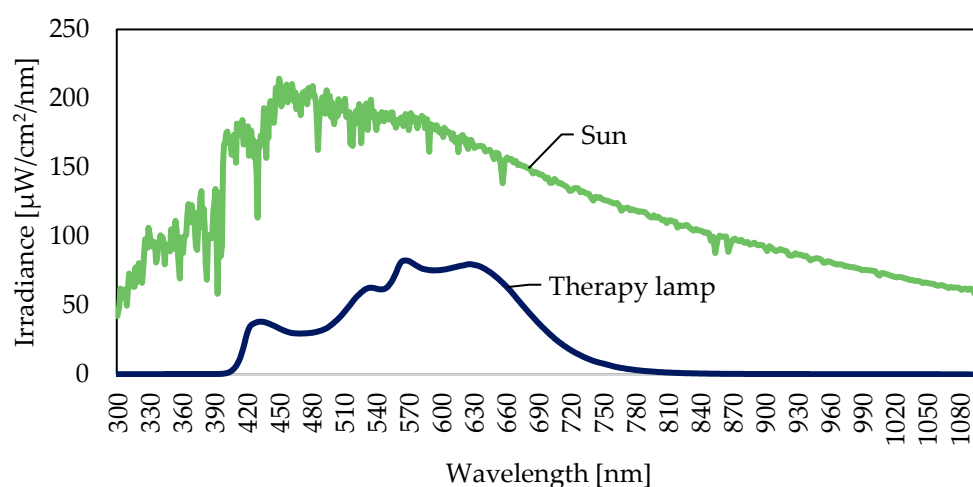


Figure 10. Bright light therapy lamp and solar spectra.

2.3. Uncertainty Analysis

As the measurements were only conducted once per sample, an uncertainty analysis was performed. The calculations use the formula for the relative uncertainty propagation, here denoted as Equation (1), as described by Kline and McClintock [30], which was derived into Equation (2) for the purposes of this study, where X is the number of thermocouples, Y the number of heat flux sensors used in the measurement in question, and the inherent error values of the K-type thermocouples and the heat flux sensors being considered to be $u_{\Delta T}/\Delta T = 0.75\%$ and $u_q/q = 0.5\%$, respectively. The resulting uncertainty margins have been added to the results of each individual measurement based on these calculations.

$$u(\lambda) = \sqrt{\sum_{i=1}^n \left(u(x_i) \frac{\partial \lambda}{\partial x_i} \right)^2} \quad (1)$$

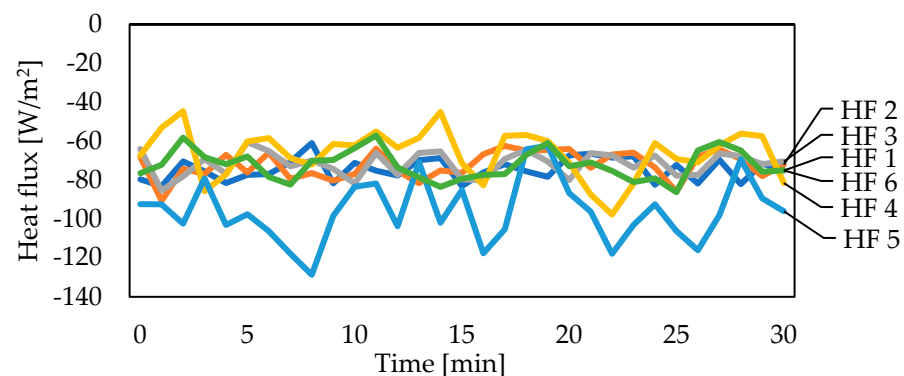
$$\frac{u_\lambda}{\lambda} = \sqrt{\left(X \frac{u_{\Delta T}}{\Delta T} \right)^2 + \left(Y \frac{u_q}{q} \right)^2} \quad (2)$$

3. Results

3.1. PV-TVIP Results

3.1.1. 2024 Measurements: Changes in Temperature and Heat Flux of TVIP and PV-TVIP

The results of the first set of TVIP and PV-TVIP measurements from 2024 [25] are gathered in Figures 11–14, with the heat flux and corresponding temperature values of each condition being placed under the same caption, heat flux figures at the top and temperature figures at the bottom. The positive and negative signs of the heat flux values correspond to the direction of the heat flow as considered from the point of view of indoor climate control, where negative values show heat loss during the simulated winter (cold) conditions, and positive values heat gain during the simulated summer (hot) conditions. The differences in values within each individual experiment was likely due to the halogen lamp acting as a spotlight, increasing the values measured by the sensors closest to the lamp. These experiments were conducted with the cold conditions first, and the hot conditions second. The averaged values for each sensor location of all conditions are collected in Figure 15. The values in Figure 15 and the following average temperature and heat flux figures of the study are formatted so that values from sensors inside the chamber are shown as the left-hand side columns, and values from sensors on the laboratory side (ambient) are shown as the right-hand side columns.



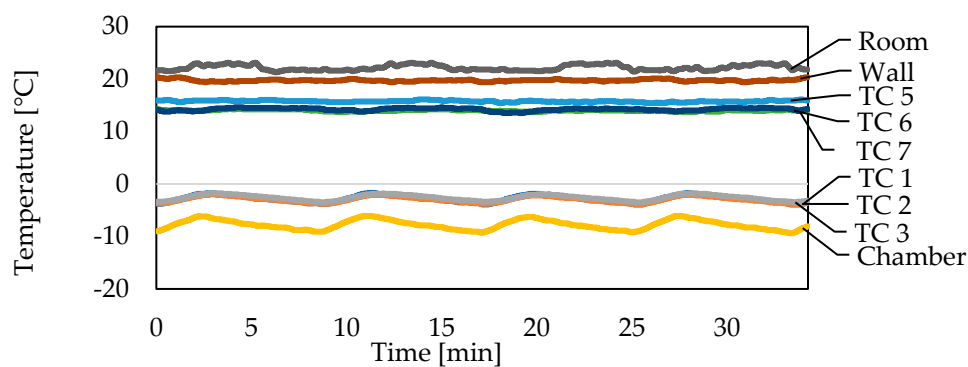


Figure 11. 2024 TVIP Cold, heat flux (**top**); temperature (**bottom**) [25].

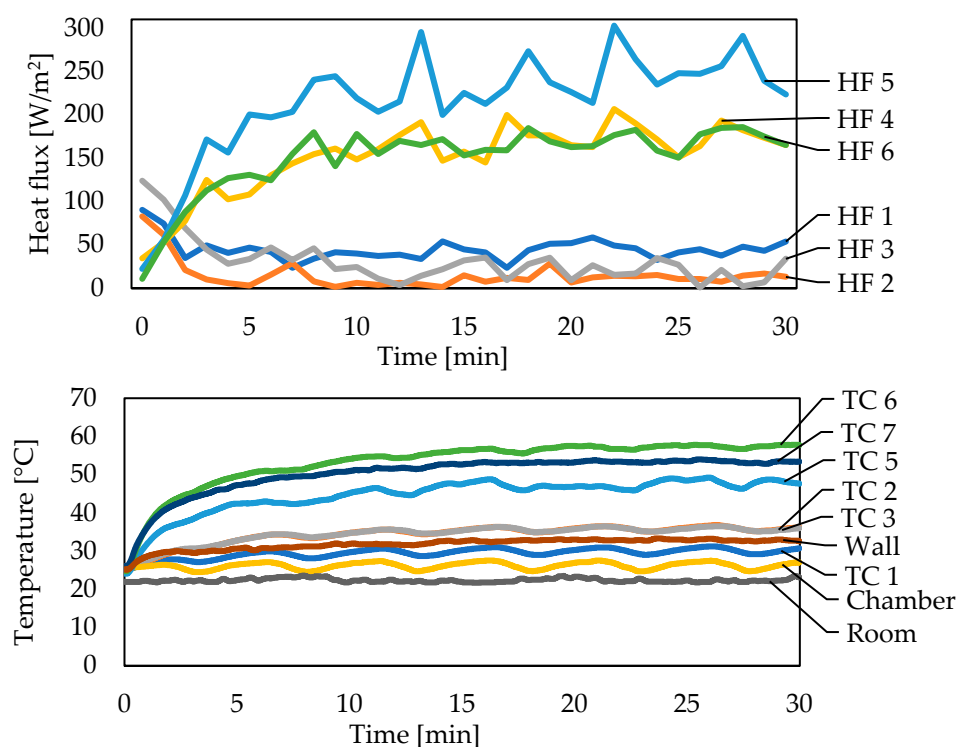
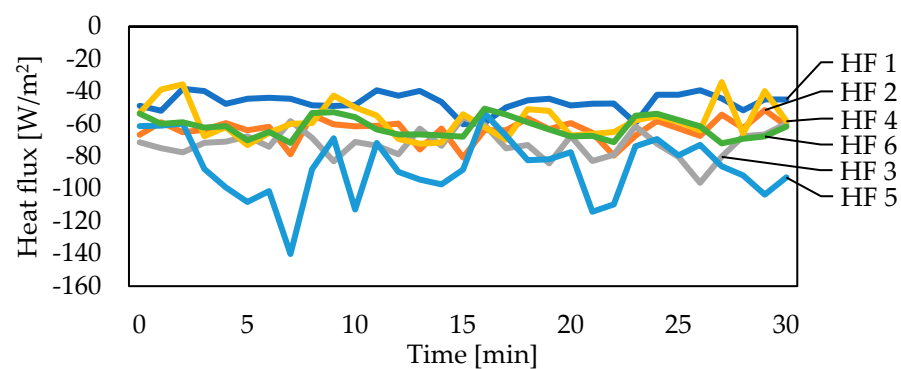


Figure 12. 2024 TVIP Hot_C, heat flux (**top**); temperature (**bottom**) [25].



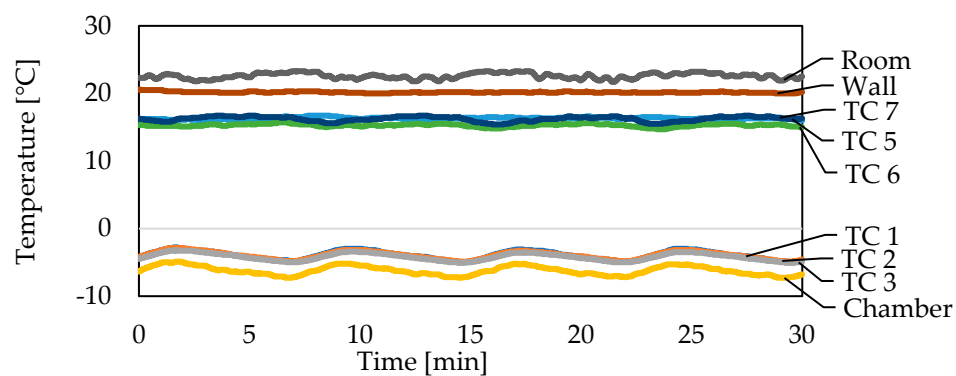


Figure 13. 2024 PV-TVIP Cold, heat flux (**top**); temperature (**bottom**) [25].

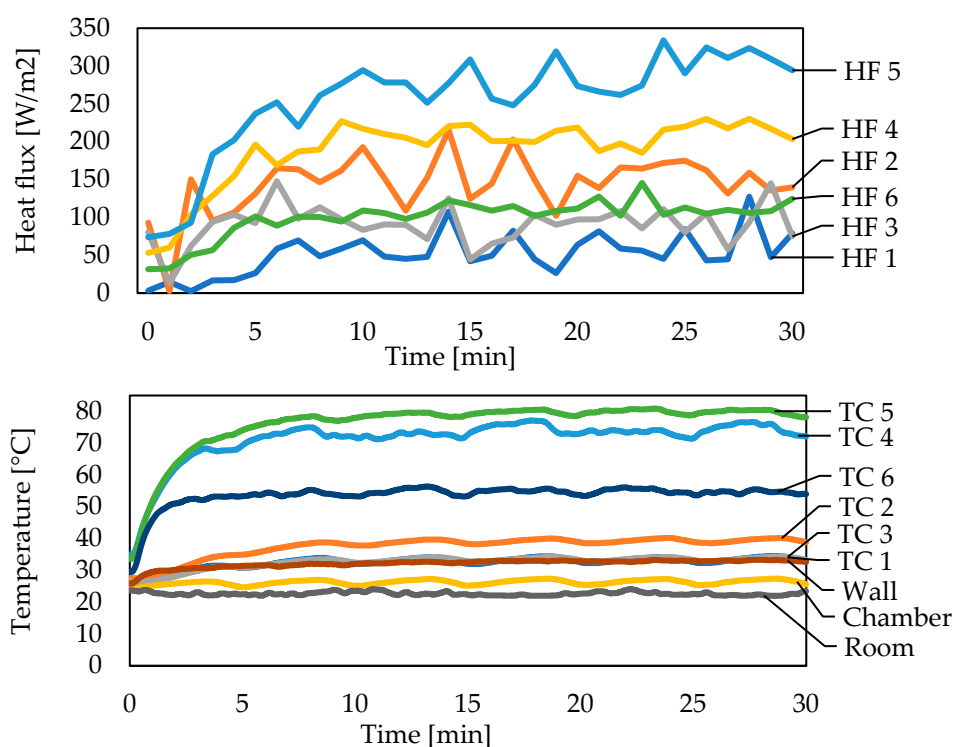
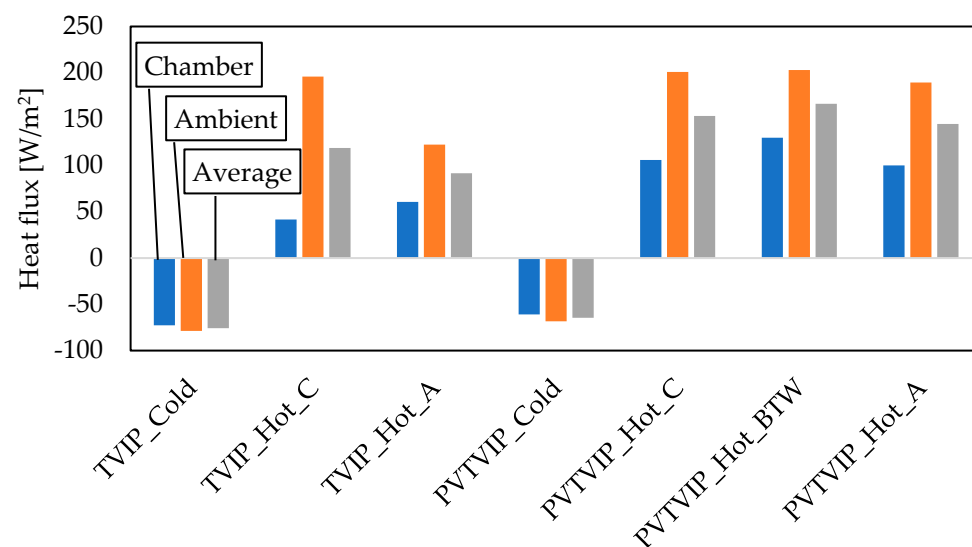


Figure 14. 2024 PV-TVIP Hot_C, heat flux (**top**); temperature (**bottom**) [25].



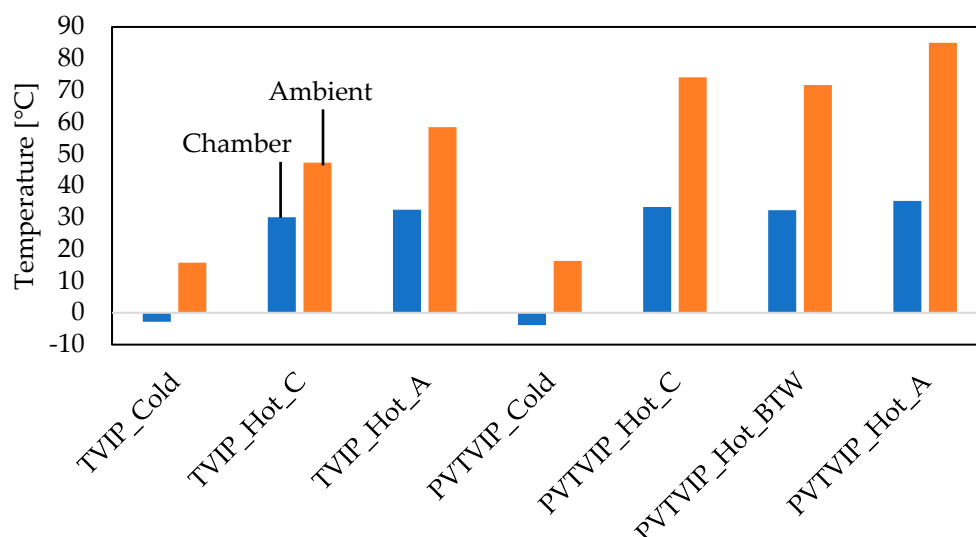


Figure 15. 2024 Measured heat flux (**top**) and temperature values (**bottom**), average over both sample faces [25].

In the cold experiments the values for both heat flux and temperature are nearly equal for TVIP and PV-TVIP at 16 °C temperature and approximately 70 W/m² heat flux gradients across the panels, which is to be expected, as without external heat source the samples are essentially equal in construction and insulation effectiveness. Changes can be observed when heat is applied, as the outside temperature values rise to 50–80 °C depending on the specific measurement being conducted. It is notable that the temperature of the chamber-side TVIP face did not experience much change even when the outside temperature increased by 60%, remaining at approximately 30 °C during each measurement. The temperature increase caused by the PV panel to the TVIP is also noticeable, as the average outside temperature increased by approximately 27 °C.

The amount of heat generated by the PV panel is measurably significant. This measurement was set up with the PV panel facing open air instead of a window glass, which likely kept the surface temperature lower than it would be when attached to a window. Knowing that the efficiency of PV panels decreases when they heat up and remembering that large, unevenly distributed heat differentials may be detrimental to the continued integrity of non-tempered glass, this could be a cause for concern that will need further investigation.

For the purposes of calculating the heat gain/loss through a TVIP, the heat flow was calculated with Equation (3):

$$Q = A \cdot q, \quad (3)$$

where Q is the heat transfer rate in W, A the area of opening in polystyrene block in m², and q the measured average heat flux in W/m². The resulting values are collected in Table 4, where $A = 0.09$ m². Remembering that the heat flow is towards the colder side, the obtained results would imply that on average a heat loss of 6–7 W occurred during the winter condition for both the TVIP and the PV-TVIP, and a 9–15 W heat gain during the summer condition measurements.

Table 4. Calculated heat flow, temperature difference, thermal conductivity, and thermal transmittance values for each individual condition.

Sample (Error Margin)	Identifier	Q [W] (±3%)	ΔT [K] (±4.5%)	λ [W/(m·K)] (±5.4%)	U [W/(m²·K)]
TVIP	C	6.82	19.3	0.01630	2.34
TVIP_H	C	10.69	18.4	0.02767	3.06
	A	8.23	26.5	0.01409	2.14
PV-TVIP	C	5.82	20.6	0.01281	1.95
PV-TVIP_H	C	13.81	42.4	0.01504	2.15
	BTW	14.98	48.7	0.01690	2.29
	A	13.03	43.9	0.01164	1.90

Thermal conductivity calculations can be conducted from the heat flux values in Figure 15 with Equation (4), where d is the thickness of the sample panel in m, q the measured heat flux value in W/m², and t_o and t_i , respectively, are the measured average outside and inside temperatures in °C.

$$\lambda = d \cdot \frac{q}{(t_o - t_i)} \quad (4)$$

The total thermal transmittance (U-value) of a TVIP attached to a single-glazed window can be estimated with Equation (5), where

- R_{SO} is the fixed external surface resistance, set to 0.06 [m²·K/W] [31];
- R_{SI} is the fixed internal surface resistance, set to 0.13 [m²·K/W] [31];
- d_{TVIP} is the thickness of the TVIP in [m], measured to be 0.004 [m];
- λ_{TVIP} are the thermal conductivity values in Table 4;
- d_{glass} is the thickness of the window glass in [m], set to 0.002 [m];
- λ_{glass} is the window thermal conductivity, set to 0.85 [W/(m·K)] [32].

$$U = \frac{1}{R_{SO} + \frac{d_{TVIP}}{\lambda_{TVIP}} + \frac{d_{glass}}{\lambda_{glass}} + R_{SI}} \quad (5)$$

The resulting values are collected in Table 4, grouped by sample type (TVIP or PV-TVIP) and subtype (hot or cold). The average calculated thermal transmittance value for the assumed TVIP + single-glazed window combination is approximately 1.9–2.3 W/(m²·K), which would decrease the glass pane U-value from that of ASHRAE standard single-glazed window [33] to rival the common value range of 1.4–2.6 W/(m²·K) [33,34] for double-glazed window thermal transmittance, potentially reaching the standard values set for triple glazed windows.

To compare the effect of seasonal changes in atmospheric humidity, the values obtained in [26] are shown in Figure 16. These measurements were conducted during autumn 2023, with the hot conditions first and the cold conditions afterwards. As with the previous results, negative values show heat loss and positive values show heat gain. The values for TVIP_Cold and PV-TVIP_Cold are approximately 30–40% larger than their 2024 counterparts shown in Figure 15, showing strong correlation with the average humidity between the ambient conditions of spring and autumn in Hokkaido. In a previous study by the authors' research group [35], it was shown that the amount of post-sealing core outgassing could be significantly reduced with prolonged heating under vacuum conditions during the sealing process, decreasing the effect of seasonal changes in ambient conditions during manufacturing.

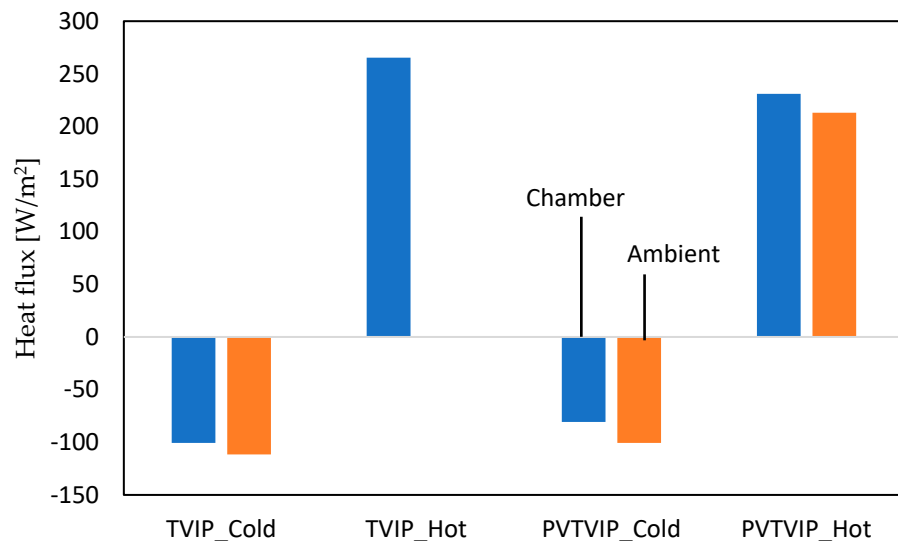


Figure 16. Measured heat flux values from 2023 [26]. Laboratory-side (ambient) sensor data in TVIP_Hot is omitted due to sensor malfunction.

The experiments regarding the order of measurement condition application were measured without the PV panel, denoted in Figure 17 as TVIP2. These measurements were conducted immediately following the measurements shown in Figures 11–15. The results from these measurements were the opposite of the authors' expected values, showing that first heating and then cooling the panel (TVIP2) produced lower heat flux values than first cooling and then heating the panel (TVIP). The exact reason for this is currently unknown to the authors; further research is currently being conducted to find the reason and ways to control for it during manufacturing.

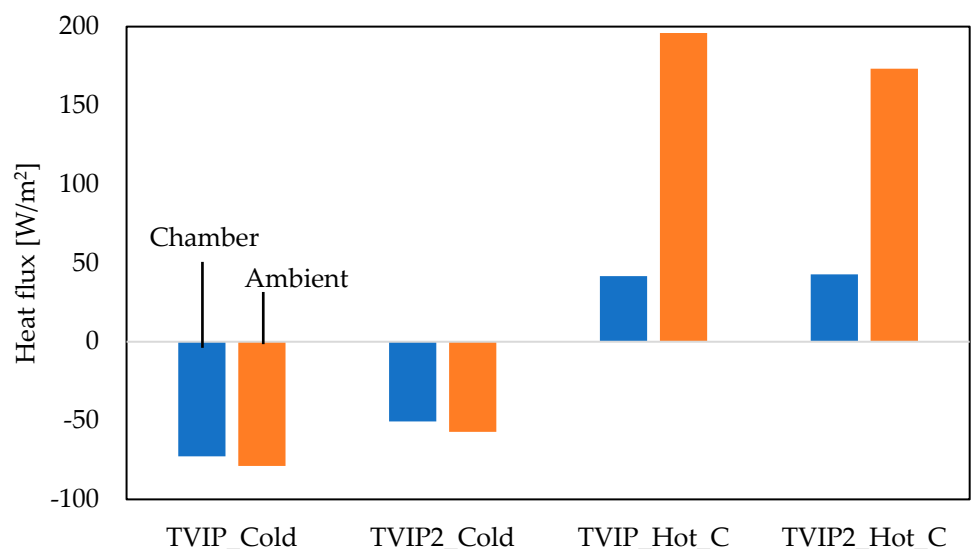


Figure 17. Comparison of measured heat flux values when the order of the hot and cold experiments is reversed [25].

3.1.2. 2025 Measurements: Increase in PV Panel Temperature, Reduction in Voltage and Power Generation

The measurements in this study were conducted within half a year from the procurement of the PV panel, and thus the panel open-circuit voltage had not yet changed from the specified V_{oc} value of 15.7 V stated in Table 2. Knowing that the electrical performance

of PV panels changes in relation to the temperature of the panel [36], the voltage of the panel was measured during the PV-TVIP HOT_C measurement with a $250\ \Omega$ resistor attached to the circuit as a simulated load. As shown in Figure 18, the measured voltage peaked at 15.4 V when the lamp was turned on, decreasing to approximately 13.3 V after 4 min. This degree of decrease roughly corresponds to the increase in temperature seen in Figure 14. The initial current of the panel was measured to be 24 mA, from which the current value decreased to 23 mA after the voltage had stabilized. The decrease in power generation can be calculated to have been from 0.38 W to 0.33 W, a decrease of 13% that roughly corresponds to the decrease in voltage.

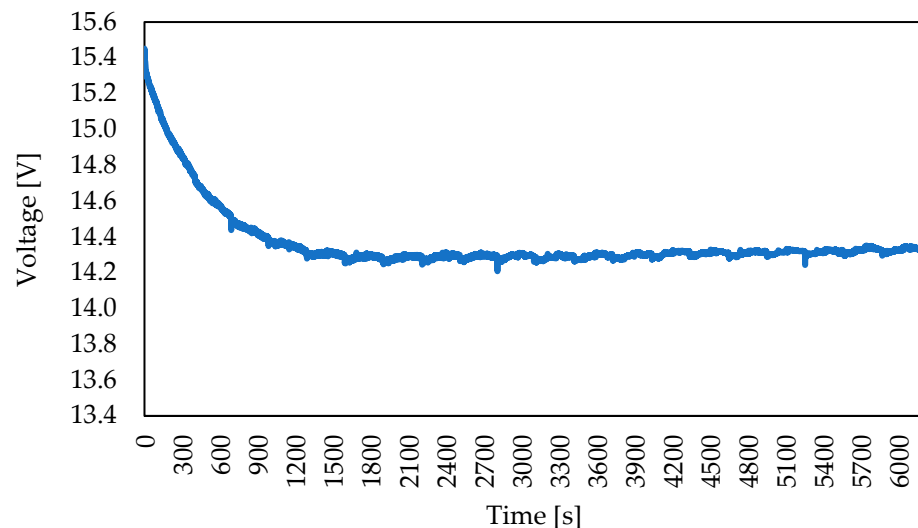


Figure 18. 2025 PV-TVIP HOT_C, voltage.

The average PV temperature and V_{oc} values for the second set of PV-TVIP measurements are shown in Figures 19 and 20. The temperature values in Figure 19 adhere to those expected by the authors, where the highest values can be found with the samples containing the TVIP. The temperature of the PV panel increased by almost 75% when installed on the inside face of a window and combined with the TVIP. Based on these measurements, the temperature did not reach values that would endanger the structural integrity of regular windowpanes so long as the PV-TVIP is installed over the whole window area so that temperature gradients across the window's area are not created.

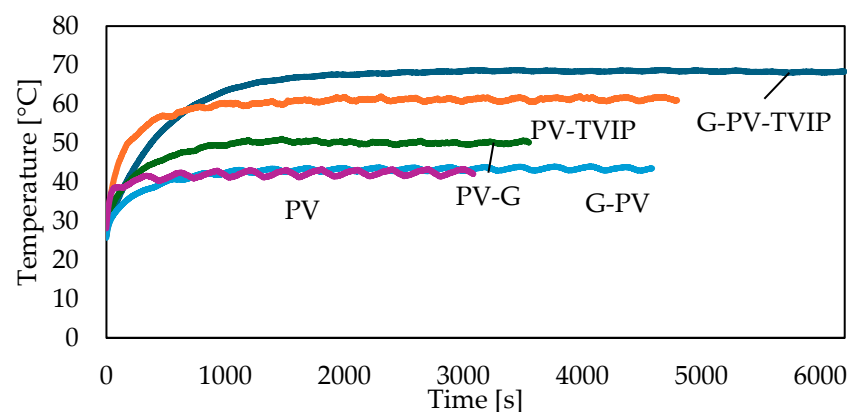


Figure 19. 2025 measured PV temperature values $\pm 6.75\%$.

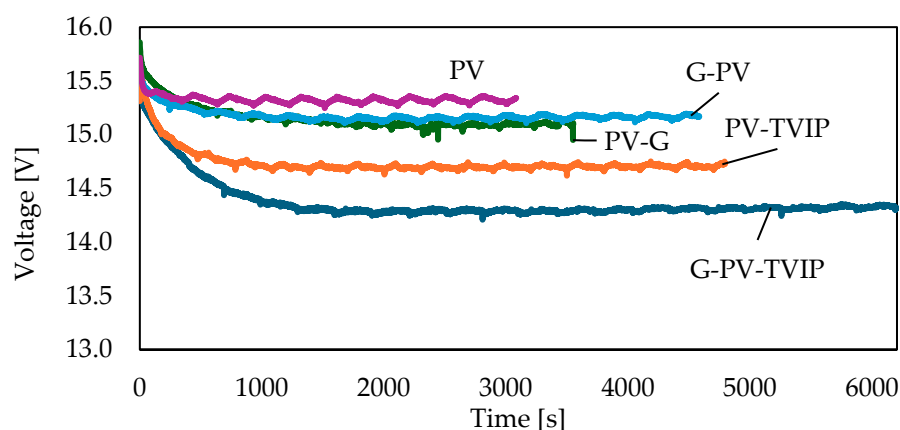


Figure 20. 2025 measured PV Voc values.

The measured voltage values of Figure 20 roughly follow the opposite pattern of the temperatures in Figure 19 outside of PV-G and G-PV having near-equal decrease in V_{oc} despite their difference in temperature. Figure 21 shows the calculated average temperature and voltage values for the last 30 min of each measurement, where the decreasing line represents voltage and the rising one temperature. The difference in voltage between just the PV panel and the G-PV-TVIP samples, the least and the most insulated samples, was exactly 1 V over a 26.06 K temperature difference. From this it can be calculated that on average, the V_{oc} of the PV panel fell by 0.038 V for each increase of 1 K in temperature.

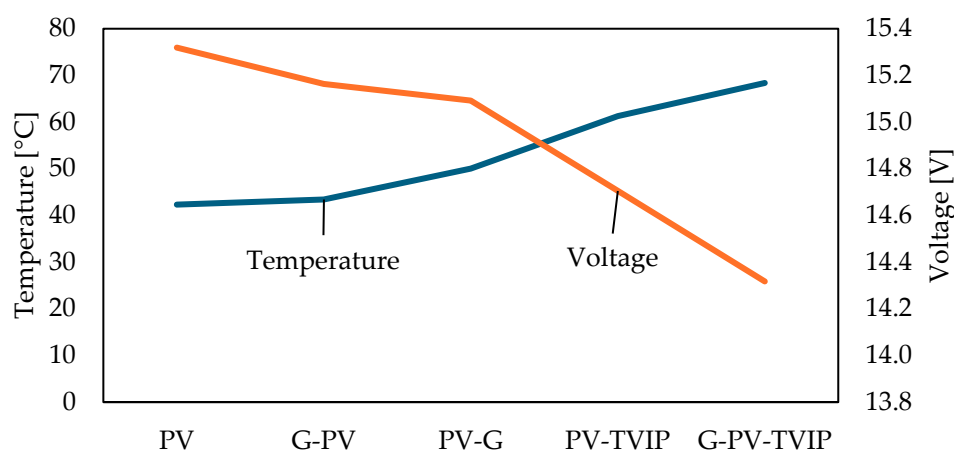


Figure 21. 2025 calculated average PV temperature and voltage of each sample composition for the last 30 min of the experiment.

3.2. Transparency Analysis Results

Measurements for the transparency analysis were taken for the regular TVIP and the PV-TVIP, where each measurement was conducted with both the therapy lamp and a UV lamp with a peak wavelength of 370 nm. Figure 22 shows the measured irradiance of the therapy lamp and the remaining irradiance when a TVIP or PV-TVIP is placed between the lamp and the sensor in the respective order from top to bottom. With the TVIP, a significant decrease can be seen in the 510–700 nm range, corresponding to a 50% decrease in green, yellow, orange, and red wavelengths of the visible spectrum, with a comparatively smaller 23% decrease seen in the 420–450 nm range corresponding to the purple color. It is thus notable that the light passing through the TVIP will be shifted towards shades blue in color when compared to the original input spectrum. With the PV-TVIP, a

decrease in irradiation of approximately 90% can be observed in most ranges outside the 430–500 nm range, which in turn had approximately 70% decreased values.

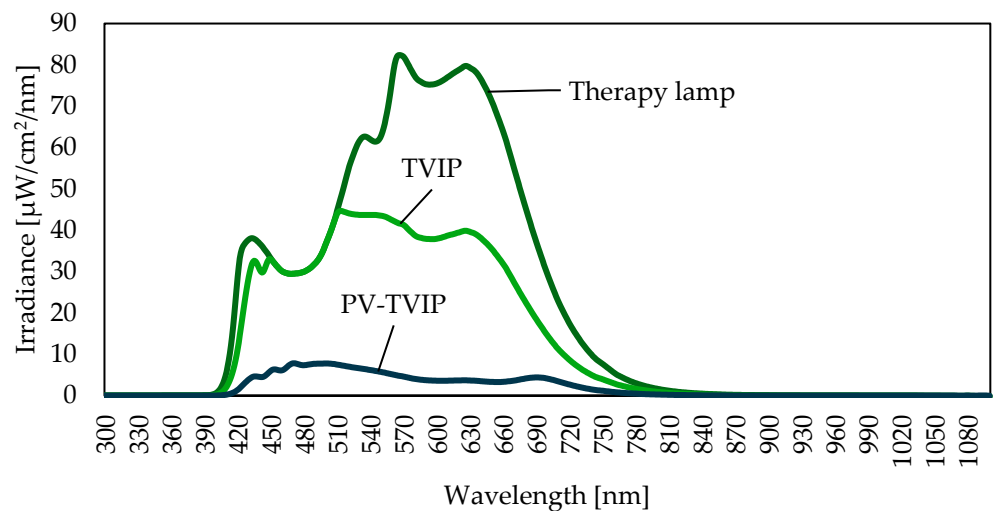


Figure 22. Comparison of pure therapy lamp spectrum to TVIP and PV-TVIP-attenuated spectra.

Figure 23 shows the effect of the TVIP and PV-TVIP on UV radiation. As can be seen, the base TVIP decreased the measured intensity by approximately 78%, while the addition of the PV panel to the TVIP completely negated all UV radiation. As UV radiation is a major cause of plastic degradation over time [37] and thus a likely major cause of increased pressure inside the TVIP, this reduction in UV radiation passing into the ABS core is likely to increase the period during which the TVIP will stay effective as an insulator.

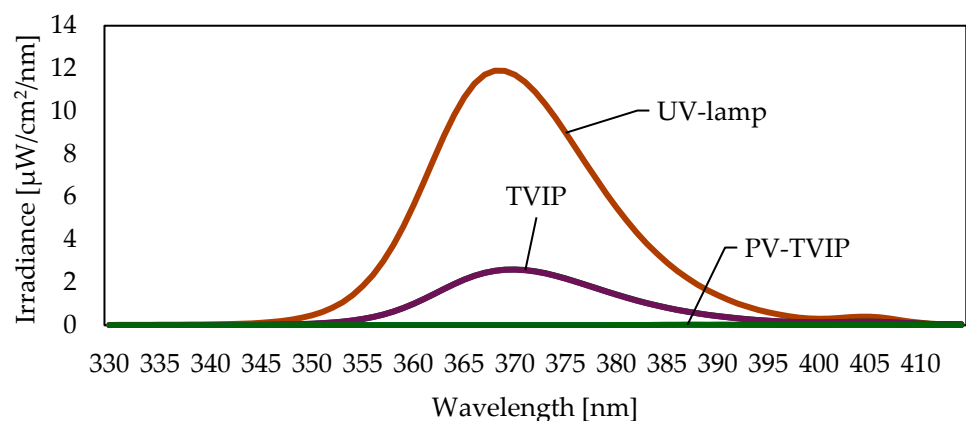


Figure 23. Comparison of pure UV lamp spectrum to TVIP and PV-TVIP-attenuated spectra.

When measuring light passing through an object, measurements are often conducted to receive the transmittance, reflection, and absorption values of the material. In the case of this study only the transmittance was considered, as the main interest was to see how much light passes, or transmits, through the TVIP. The transmittance values of the panels were calculated based on Equation (6), where $E_{e,s}$ and $E_{e,l}$ are the measured irradiance values for the panels and just the lamp itself, respectively. Values for transmittance as percentage fractions of the unhindered intensity were calculated across separate ranges of the visible light spectrum according to their wavelength ranges shown in Figure 24,

where the values for TVIP are shown as the left-hand-side orange bars, and the values for PV-TVIP as the right-hand-side blue bars.

$$T = \frac{E_{e,s}}{E_{e,l}} \cdot 100 \quad (6)$$

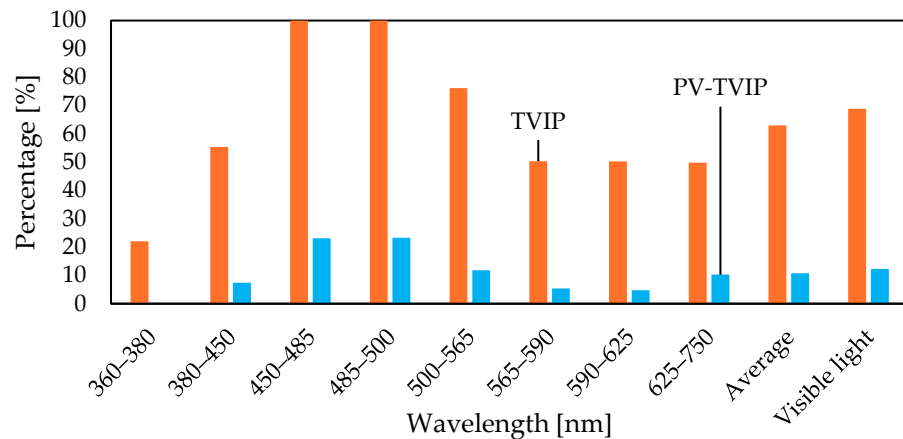


Figure 24. TVIP and PV-TVIP radiation transmittance, percentage fractions of unhindered intensity.

4. Discussion

4.1. PV-TVIP

The measurements in this study work as a proof of concept for adding a PV panel to the TVIP, creating a lightweight BAPV solution. The heat flux and temperature values across the panels were measured under simulated winter and summer conditions corresponding to the average conditions in Sapporo, Japan. In the summer condition measurements, the halogen lamp was placed perpendicular to the panels, a situation that TVIP would rarely experience when installed onto the assumed use case of a regular window. The increased temperatures measured during these experiments are thus assumed to be an example of a worst-case scenario insofar as temperature differences go. The measurements showed that attaching a TVIP to a single-glazed window would decrease the window's thermal transmittance to values close to those common for double-glazed windows. The main points of the PV-TVIP measurements can be summarized as follows:

- TVIP with ABS plastic as the core material is susceptible to changes in thermal conductivity depending on the humidity of the manufacturing environment. It is therefore desirable to conduct core manufacturing in a climate-controlled environment with low humidity.
- When compared to earlier studies, the effect of increased core volume in this study can be seen in the thermal conductivity values. This can be mitigated by added measures against atmospheric humidity such as heating during the vacuum sealing process.
- The calculated heat gain/loss values for both TVIP and PV-TVIP were approximately 6–7 W heat loss during winter condition measurements and 9–15 W heat gain during summer condition measurements.
- The order of the heating and cooling experiments has a measurable albeit negligible effect, where the sample that was heated first and then cooled had lower heat flux values than the one that was cooled and then heated.
- In the setup used in this study, attaching a PV panel to a TVIP increased the operating temperature of the PV panel by approximately 19 °C with a further increase of approximately 7 °C when attached to the glass pane. This increase in operating temperature decreased the PV panel's voltage by 2.1 V in the case of the full PV-TVIP, re-

ducing the PV power generation by 13%. As a warning, the halogen lamp used in this study likely added more heat to the system than would be expected in an in situ installation.

The authors acknowledge that the variability and error margins in the measurements of the current study are relatively large due to the present form of fully manual manufacturing process and single measurements per sample. An error margin of 10% was deemed reasonable for these measurements to reliably serve as a proof of the concept of PV-TVIP viability, a limit under which all the measured values stayed. This can be confirmed by comparison of the obtained values between PV-TVIP_Hot_C and PV-TVIP_Hot_BTW in Figure 15 as well as those obtained between TVIP and TVIP2 in Figure 17, as these measurements are essentially identical to each other. Further experiments will be conducted based on international standards so that TVIP values can be compared to experimental results received outside of the author's research group.

4.2. Transparency Analysis

Based on the transparency measurements, the base TVIP reduces the amount of UV radiation between 360 and 380 nm by approximately 78%, and most visible light wavelengths between 380 and 750 nm by approximately 45–50%. Blue and cyan light are the least affected, both passing through the panel essentially unhindered, while green light loses only a quarter of its intensity. PV-TVIP attenuated most visible light by 88–95%. Based on this, the TVIP used in this study reduced incoming solar radiation by 37% and the PV-TVIP by 89%. If UV radiation is disregarded, the TVIP reduced the amount of visible light passing through the window by 31% and the PV-TVIP by 87%. Two things must however be noted regarding this experiment. Firstly: These values are highly dependent on the specific core geometry being used—as smaller gaps in the lattice structure will inherently block more radiation—and the transparency of the other components chosen for a specific TVIP. While full transparency is preferred, any additional layer of material will inherently distort visibility. Secondly: The measured wavelengths and their relative intensities produced by the therapy lamp were not identical to direct solar radiation. This should not cause major issues regarding the measurements themselves as the goal of the study was to see the relative decrease in intensity instead of measuring absolute decrease, but this difference in intensity should still be kept in mind when considering the results.

5. Conclusions

In this article, two related issues were studied. Measurements were conducted on TVIP an PV-TVIP to gain data on the produced heat flux and temperature values under strong thermal radiation. In the latter section, measurements were conducted to determine the transparency of TVIP and PV-TVIP at different wavelengths of visible and UV light. During the summer condition experiments, the temperature on the chamber-facing surface of the panels stayed between 30 and 35 °C for both TVIP and PV-TVIP, while the laboratory-side temperatures ranged between approximately 50 °C for the TVIP and 75–80 °C for the PV-TVIP. Both panels maintained a surface temperature of approximately 16 °C during the winter condition measurements. The calculated thermal conductivity values for the panels largely remained between 0.011 W/(m·K) and 0.016 W/(m·K) between conditions. It was also noted that atmospheric conditions during manufacturing of the panel and the order of the measurements influenced the results, both of which can be addressed by careful climate control of the manufacturing process.

The effect of temperature on open-circuit voltage was measured for the combinations outlined in the section of this study explaining the physical measurements conducted in May of 2025. Installing the PV panel between the TVIP and the glass pane increased the

PV panel's temperature from 42.29 °C to 68.35 °C, an increase of 26.06 °C. This increase in temperature will likely not cause issues with window glazing structural integrity if the PV-TVIP covers the whole window area, decreasing temperature differences across the windows' surface areas. Calculating the decrease in V_{oc} per temperature unit results in the value of 0.038 V/K for the PV panel used in this study. The increased PV operating temperature caused the PV's voltage under a 250 Ω load to decrease from 15.4 V to 14.32 V with a corresponding decrease of 13% in power generation.

The transparency measurements showed that the TVIP reduced the amount of most visible light wavelengths longer than 500 nm by approximately 50%, while also reducing the amount of transmitted UV light by 78%. PV-TVIP on the other hand reduced wavelengths longer than 500 nm by 90%, and the ones between 380 and 500 nm by 76%. The added PV panel also completely blocked any UV radiation from passing through. Since the PV completely absorbed or reflected UV wavelengths, it has been confirmed that adding the PV to the TVIP construction prevents the TVIP components from being exposed to UV rays and subsequently its performance from deteriorating.

Author Contributions: Conceptualization, T.K.; methodology, E.H. and T.K.; formal analysis, E.H.; investigation, E.H.; resources, T.K.; data curation, E.H.; writing—original draft preparation, E.H.; writing—review and editing, E.H. and T.K.; visualization, E.H.; supervision, T.K.; project administration, T.K.; funding acquisition, T.K. All authors have read and agreed to the published version of the manuscript.

Funding: This work was supported by JST SPRING, Grant Number JPMJSP2119.

Data Availability Statement: The raw data supporting the conclusions of this article will be made available by the authors on request.

Acknowledgments: The authors thank Mitsubishi Chemical Corporation and Teijin Frontier Co., Ltd. for their assistance in the VIP test production.

Conflicts of Interest: The authors declare no known conflicts of interest. The funders had no role in the design of the study; in the collection, analyses, or interpretation of data; in the writing of the manuscript; or in the decision to publish the results.

Abbreviations

The following abbreviations are used in this manuscript:

BAPV	Building-attached Photovoltaic
BIPV	Building-integrated Photovoltaic
PV	Photovoltaic
SAD	Seasonal Affective Disorder
TVIP	Transparent Vacuum Insulation Panel
ABS	Acrylonitrile–Butadiene–Styrene
PET	Polyethylene Terephthalate
UV	Ultraviolet

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