Determination of Heat Gain through Different Types of Building-Integrated Photovoltaic Façade Combined with Phase Change Material and Smart Glazing

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Abstract. This study aims to design and evaluate the thermal performance of an intelligent building glazing system that integrates building-integrated photovoltaic (BIPV), phase change material (PCM), and smart glazing (SG) technologies to enhance building energy efficiency. The system comprises semi-transparent solar cells for electricity generation, a PCM layer for absorbing and releasing latent heat, and SG for dynamic optical control. The research employed theoretical calculations under steady-state conditions to compare six window configurations under typical tropical conditions. The results showed that the BIPV-PCM-SG system in off mode achieved the lowest overall heat transfer coefficient (U-value) of 2.67 W/m^2·K and reduced heat gain to only 389.73 W, representing a 56% reduction in transmitted heat compared to a conventional clear glazing window. These results highlight the synergistic effect of combining solar energy conversion, latent heat buffering, and optical modulation. The findings establish a fundamental design basis for low-energy buildings and promote the Net-Zero-Energy Building concept, which aligns with Thailand's sustainable energy policies. This research provides a foundational guideline for designing future energy-efficient façades in tropical climates.

Keywords: Building-integrated photovoltaic; Heat gain; Phase change material; Polymer dispersed liquid crystal; Solar energy; Thermal performance

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1 Introduction

The building envelope is a significant factor in determining overall energy performance and thermal comfort inside the built environment. Global data indicate that buildings consume approximately 30% of total energy and contribute around 26% to carbon dioxide emissions [1]. This finding aligns with the Working Group III (WGIII) contribution to the Intergovernmental Panel on Climate Change's (IPCC) Sixth Assessment Report (AR6), which highlights that improving building envelopes significantly contributes to reducing greenhouse gas emissions as well as achieving low-energy and net-zero energy building designs [1].

In Southeast Asia, the demand for space cooling has become a significant factor in the rising consumption of electricity. Cooling systems currently consume around 16% of the total building electricity consumption. The percentage could increase to 30% by 2035 if no effective mitigation measures are taken [2]. Among tropical countries, Thailand has experienced steadily growing energy demand caused by rapid economic development and climate change. In 2024, national electricity consumption reached 214,469 GWh, marking a 5.2% increase compared to the previous year. This gradual growth underscores the urgent need to reduce building energy loads while simultaneously increasing the proportion of clean energy [2]. Additionally, this approach aligns well with the Organisation for Economic Co-operation and Development's clean energy investment plan, which prioritizes small-scale renewable energy and building energy efficiency. It also supports the Alternative Energy Development Plan's goal of increasing the share of renewable and alternative energy to 30% of total final energy consumption by 2037 [3].

Intelligent building envelope systems have gained increasing attention as a promising strategy for enhancing energy efficiency and reducing greenhouse gas emissions while maintaining indoor comfort. In this context, advanced façade technologies, such as smart glazing (SG) systems with controllable optical properties, enable dynamic modulation of solar radiation and daylight. Numerous studies have shown that electrochromic, thermochromic, and gasochromic glazing systems effectively reduce cooling loads while maintaining visual comfort [4]. Furthermore, case studies have demonstrated that properly optimized gasochromic glazing can substantially reduce building energy consumption [5]. At the same time, the integration of photovoltaic (PV) technology into building components has led to the emergence of building-integrated photovoltaic (BIPV) and building-integrated photovoltaic-thermal (BIPV-T) systems, which allow buildings to generate electricity while allowing natural daylight [6]. However, a significant challenge arises from high panel temperatures in hot and humid climates, which reduce electrical efficiency by approximately 0.4–0.5% for each °C rise above standard test conditions [7]. This has led to the development of passive thermal management strategies, such as air gaps and phase change materials (PCM), to reduce and absorb temperature fluctuations [8, 9]. Recent studies have advanced these concepts by developing double-sided PV systems using thermochromic materials and dual-layer PCM to simultaneously control heat and light. Additionally, Transparent BIPV façades have been optimized to balance electrical energy production, natural lighting, and glare control [10]. BIPV combined with PCM reduces peak temperatures by 6–11°C and decreases heat gain entering the room by 93.6%, indicating excellent thermal insulation over clear glazing [11]. Moreover, the integration of BIPV with SG represents a multifunctional glazing system that generates electricity, controls light transmission, and manages thermal loads within a single system. According to the results reported by Aritra et al. (2019), light could be transmitted through transparent glazing by approximately 46.5%, while 31.5% could be transmitted through opaque glazing. As a result, the solar cell temperature reaches 86°C in opaque mode, which is approximately 8% higher than in transparent mode [12]. The results demonstrate effective control over both light and heat. The transparent mode helps

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lower panel temperatures, reduces heat gain, and enhances electricity generation efficiency. In contrast, the opaque mode balances the entry of light and heat into the building in the case of low light [12]. These combinations offer a promising method for developing self-powered SG systems designed for future energy-efficient buildings. These window systems reduce cooling loads and electricity consumption by minimizing solar heat gain, thereby lowering operating costs and contributing to the transition toward net-zero energy buildings.

To the best of our knowledge, no research has yet integrated all three technologies into a single integrated façade system. To address this gap, this study aims to design and investigate a building envelope system that combines BIPV, PCM, and SG technologies to comprehensively evaluate energy performance in terms of temperature control. The study evaluates heat transfer based on overall heat transfer coefficient (U-value), solar heat gain coefficients (SHGC), and total heat gains under steady-state conditions compared with conventional glazing. The findings are expected to provide a practical foundation for advancing energy-efficient building design in Thailand and represent an important step toward realizing the Net-Zero-Energy Building concept, which is aligned with national energy policy and future sustainable development goals.

2 Methodology

2.1 System Configuration

This study focuses on the theoretical calculations of an intelligent building envelope system integrating BIPV, PCM, and SG technologies compared with conventional glazing. Six case studies were designed using identical prototypes sizing of 30 × 30 cm to predict the thermal performance. The layer configuration of the envelope system is summarized in Table 1. The system is designed to generate electricity, store and regulate thermal energy, and control light transmission into the building. Table 2 lists the thermo-physical properties of materials used in the building envelope system. The outermost layer consists of semi-transparent BIPV panels that convert solar radiation into electrical energy. The middle layer is composed of n-docosane PCM (Table 3), which absorbs and releases latent heat from the BIPV panels to reduce temperature fluctuations reaching the building interior. An air gap is included to enhance the thermal resistance (R-value) and reduce heat and moisture transfer. The innermost layer consists of SG with adjustable transparency to regulate the incoming light levels. The SG operates in two modes: off and on modes. In off mode, there is no electricity applied to the SG, which keeps the film opaque with low light transmission. This mode could reduce the SHGC and minimize heat gain. In on mode, electricity is applied to the SG, causing the film to become transparent and allowing natural daylight to enter. Therefore, switching between off and on modes according to weather conditions can effectively reduce heat gain entering the building. Collectively, these integrated layers aim to optimize building energy performance and substantially reduce heat gain.

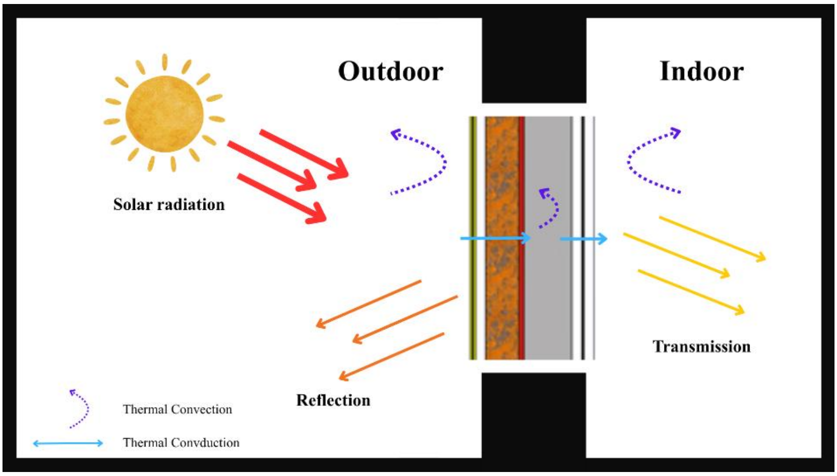


Fig. 1. Heat flow through the window.

Fig. 1 illustrates the heat transfer mechanisms through the BIPV-PCM-SG window. Incident solar radiation is partly reflected at the outer surface, while the remaining fraction is absorbed by the PV, PCM, and glazing layers or transmitted into the building interior. The absorbed energy increases the temperature of the window components and is transferred by conduction through the layers and air gap, as indicated by the horizontal blue arrows. At the outer and inner surfaces, convective heat transfer occurs between the window surfaces and the air, as shown by the dashed purple arrows. Finally, a portion of the solar radiation and heat is transmitted into the indoor side, represented by the yellow arrows. These combined processes are represented in the U-value and heat gain used in the thermal performance analysis of this study.

Table 1. Configurations of the studied window systems.

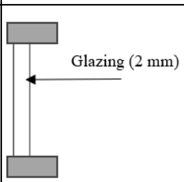
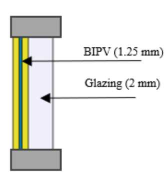
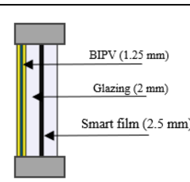
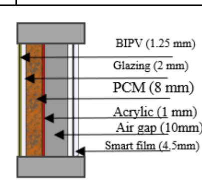
Window type	Clear glazing window	BIPV window	BIPV-SG window	BIPV-PCM-SG window
Layer composition				
Total thermal resistance	$\frac{1}{h_o}$ $\frac{L_g}{k_g}$ $\frac{1}{h_i}$	$\frac{1}{h_o}$ $\frac{L_E}{k_E}$ $\frac{L_C}{k_C}$ $\frac{L_E}{k_E}$ $\frac{L_g}{k_g}$ $\frac{1}{h_i}$	$\frac{1}{h_o}$ $\frac{L_E}{k_E}$ $\frac{L_C}{k_C}$ $\frac{L_E}{k_E}$ $\frac{L_g}{k_g}$ $\frac{L_{PDLC}}{k_{PDLC}}$ $\frac{L_g}{k_g}$ $\frac{1}{h_i}$	$\frac{1}{h_o}$ $\frac{L_E}{k_E}$ $\frac{L_C}{k_C}$ $\frac{L_E}{k_E}$ $\frac{L_g}{k_g}$ $\frac{L_{PCM}}{k_{PCM}}$ $\frac{L_{Acr}}{k_{Acr}}$ $\frac{1}{h_{air}}$ $\frac{L_g}{k_g}$ $\frac{L_{PDLC}}{k_{PDLC}}$ $\frac{L_g}{k_g}$ $\frac{1}{h_i}$
Total thickness (mm)	2.00	3.25	5.75	26.75

Table 2. Thermal and physical properties of materials used in the building envelope system.

Materials	Thermal conductivity (W/m·K)	Thickness (mm)
Encapsulant	0.23	0.50
Monocrystalline cell	148	0.25
Glass	0.98	2.00
N-docosane ($C_{22}H_{46}$)	0.24	8.00
Acrylic	0.19	1.00
Air gap	6.67	10.00
Polymer dispersed liquid crystal film	0.10	0.50

Table 3. Thermal and physical properties of the n-docosane PCM [13]

Melting point (T_M) (°C)	Thermal conductivity (k) (W/m·K)	Latent heat (L) (kJ/kg)	Density (ρ) (kg/m^3)
42–45	0.24	249	794.4

2.2 Thermal Performance Analysis

The study focused on calculating the thermal performance by comparing the heat gain and overall heat transfer coefficient across six window configurations under steady-state conditions. The analysis employed environmental conditions typical of Thailand as follows: an average ambient temperature of 38°C, an indoor room temperature of 25°C, a window area of 0.09 m^2, and a solar irradiance of 1,000 W/m^2. The following environmental parameters were maintained as constant values throughout the analysis of each window type [11, 14]. The indoor heat gain (Q_{in}) was computed from one-dimensional steady-state heat transfer, as shown in Equation 1. The SHGC is the fraction of incident solar radiation that enters through the glazing, as revealed in Equation 2. The value of SHGC ranges from 0 to 1, with 1 corresponding to an opening in the wall with no glazing. The U-value was obtained from layer thermal resistances, which can be calculated according to Equations 3 and 4. The total thermal resistance (R-value) represents the sum of thermal resistances of all layers and describes the ability of the window system to resist steady-state one-dimensional heat flow. A higher R-value corresponds to a lower U-value, indicating better insulation performance and reduce heat gain.

$$Q_{in} = U \cdot A_{Window} \cdot [(T_{outside} - T_{room}) + SHGC \cdot G_{solar}] \quad (1)$$

$$SHGC = \tau_{sol} + \phi \cdot \alpha_{sol} \quad (2)$$

$$R_{tot} = \frac{1}{h_o} + \Sigma_i \frac{L_i}{k_i} + \frac{1}{h_i} \quad (3)$$

$$U = \frac{1}{R_{tot}} \quad (4)$$

Where Q_{in} is the indoor heat gain through the window (kJ), U is the overall heat transfer coefficient (W/m^2·K), A_{window} is the area of the window (m^2), $T_{outside}$ is the outside temperature (°C), T_{room} is the room temperature (°C), $SHGC$ is the solar heat gain coefficient, G_{solar} is the solar irradiance (W/m^2), τ_{sol} is the total transmitted solar, ϕ is the inward flowing fraction, α_{sol} is the solar absorptance, R_{tot} is the total thermal resistance of the wall (m^2·K/W), h_0 is the outside heat transfer coefficient (W/m^2·K), L_i is the i-th layer thickness of the wall (m),

K_i is the thermal conductivity at i-th layer (W/m·K), h_i is the inside heat transfer coefficient (W/m^2·K).

According to ISO standards, the outside and inside surface thermal resistances are recommended to be 0.04 and 0.13 m^2·K/W, respectively. These values can be derived from the external and internal heat transfer coefficients, which are defined for specific boundary conditions as 25 and 7.69 W/m^2·K, respectively. In addition, the thermal resistance of a 10 mm air layer is taken as 0.15 m^2·K/W, corresponding to an air-gap heat transfer coefficient of 6.67 W/m^2·K under the same boundary conditions [15].

3 Results and Discussions

The comparative thermal performance of the six glazing configurations, namely clear glazing, BIPV glazing, BIPV-SG (off/on), and BIPV-PCM-SG (off/on), was evaluated under identical steady-state boundary conditions. The corresponding U-value, SHGC, and total heat gains are summarized in Table 4. The overall heat transfer coefficient, calculated in W/m²·K, indicates the insulation effectiveness of the window system, with a lower U-value indicating better insulation performance. Heat gain, expressed in W, represents thermal energy entering the building interior. Therefore, the U-value and heat gain should be kept as low as possible to minimize heat passage into buildings.

Table 4. Comparative thermal performance parameters of various façade configurations.

Case	Total thermal resistance (m^2·K/W)	Overall heat transfer coefficient (W/m^2·K)	SHGC	Heat gain (W)
Clear glazing window	0.175	5.70	0.88	886.67
BIPV window	0.178	5.56	0.64	642.51
BIPV-SG window (on)	0.187	5.35	0.56	566.08
BIPV-SG window (off)	0.187	5.35	0.40	407.86
BIPV-PCM-SG window (on)	0.374	2.67	0.54	547.95
BIPV-PCM-SG window (off)	0.374	2.67	0.39	389.73

As listed in Table 4, the clear glazing window exhibited the lowest thermal performance, with a U-value of 5.70 W/m^2·K, resulting in the highest heat gain of 886.67 W. For the BIPV window, the U-value was 5.56 W/m^2·K with a heat gain of 642.51 W. When examining the BIPV-SG window system, the system performance depended strongly on its operating mode. Although both modes have the same U-value of 5.35 W/m^2·K, the difference in heat gain highlights a significant reduction in heat transfer by 54% in the off mode. In the on-mode, the film becomes transparent, resulting in an increase in solar transmittance and raising the heat gain up to 566.08 W. In contrast, in the off-mode, where the film becomes opaque and scatters incident radiation, the heat gain drops to 407.86 W. This is because the off mode renders the film opaque and scatters more sunlight, leading to a decrease in direct solar transmittance. While the same U-value is maintained, this advantage results in a lower SHGC [11]. Finally, the BIPV-PCM-SG window system, which integrates all three technologies, achieved a substantially reduced U-value of only 2.67 W/m^2·K. In the off mode, this configuration delivered the best performance in preventing heat transfer into the building with a heat gain of 389.73 W, while in the on mode achieved a heat gain of 547.95 W. This improvement results from the combined effect of several components. The PCM and the air gap lower the U-value, while the latent heat absorption property of the PCM delays heat flow [12]. Additionally, the BIPV layer converts a portion of the incoming solar energy into electricity [12], and SG in off mode further reduces solar transmittance. Collectively, these factors help reduce the heat gain, SHGC, and U-value [11].

Therefore, the integration of all three technologies in the BIPV-PCM-SG system operating in off mode can reduce heat gain by up to 56% compared to clear glazing. This demonstrates the significant potential of this design approach for minimizing thermal energy entering building interiors.

The results showed that BIPV windows designed to reduce heat gain entering the building should be configured with the PV layer positioned as the outermost layer. This layer converts a portion of the incoming solar energy into electricity and reduces solar radiation entering the building. The middle layer should consist of PCM or an air gap to increase the R-value. The PCM absorbs and releases latent heat, which delays heat flow into the building interior. Finally, the SG layer should be installed as the innermost layer and operated in off mode during high solar irradiance to reduce solar transmittance. This mode allows the film to become opaque and scatters incident radiation, while still allowing light transmission to be adjusted according to indoor lighting requirements. The BIPV–PCM–SG system represents an effective design approach for reducing heat gain.

4 Conclusion

This study successfully evaluated and compared the thermal performance of various types of smart window systems through theoretical calculations under steady-state conditions. The results reveal that the hybrid BIPV-PCM-SG system exhibits significantly enhanced insulation performance as compared with conventional glazing. The U-value decreased from 5.70 $W/m^2{\cdot}K$ for clear glass to 2.67 $W/m^2{\cdot}K$ for the hybrid BIPV-PCM-SG configuration, while the total heat gain was reduced by 56% from 886.67 W to 389.73 W in the off mode. This approach represents a pathway toward developing and enhancing building energy efficiency while reducing carbon dioxide emissions. These technologies also function to generate electrical energy and control solar radiation entering the building, while simultaneously controlling passive thermal regulation, which directly contributes to cooling load reduction and indoor thermal stability. Future studies should also investigate transient thermal simulations to model heat transfer throughout the day. Overall, this research introduces a conceptual framework for the design of low-energy and net-zero-energy façade systems in tropical climates. The findings contribute to the advancement of sustainable building technologies aligned with Thailand's national energy transition and carbon reduction goals.

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