Effects of Smart Polymer-dispersed Liquid Crystal Window Film on Indoor Environment and Air-conditioning Electricity Consumption of Buildings in Taiwan

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In this study, the authors investigated the smart polymer-dispersed liquid crystal (PDLC) window film as an innovative building envelope technology supporting Taiwan's 2050 Net-Zero Emissions Pathway through comprehensive laboratory characterization, durability assessment, full-scale experimentation, and building energy simulation. Laboratory measurements demonstrated dynamic optical performance with visible light transmittance varying from 87.68% (transparent state) to 61.07% (shading state) and solar heat gain coefficient ($SHGC$) decreasing from 0.8246 to 0.6630, achieving a 16.16% solar heat gain reduction. Durability testing validated stable optical properties after 8000 switching cycles and accelerated weathering equivalent to five years under Taiwan's climate conditions. Full-scale building experiments confirmed 5% air-conditioning energy consumption reduction in the shading state while maintaining optimal indoor illuminance between 500 and 700 Lux through an occupant-centric control system. Building energy simulation using Taiwan's Building Energy Simulation Tool with Artificial Intelligence (BESTAI) platform revealed significant synergistic effects, with the comprehensive integration of PDLC technology, occupancy-based lighting control (35% energy reduction), and high-efficiency heating, ventilation, and air-conditioning (HVAC) systems (15% reduction) achieving cumulative 52% total energy savings, where PDLC contributed an additional 2% savings beyond other efficiency measures. Thermal environment monitoring demonstrated that the shading state created a delayed thermal response, effectively reducing direct radiative heat transfer to interior spaces. These findings validate the smart PDLC window film as a viable multi-functional solution offering simultaneous benefits in energy efficiency, thermal comfort optimization, visual quality enhancement, dynamic privacy control, and retrofit applicability for existing buildings, contributing to building sector decarbonization goals.

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1. Introduction

In response to the global threat of climate change, the international community is engaged in a collaborative effort to achieve the goal of net-zero carbon emissions by 2050. This initiative aims to address the adverse effects of climate change and stabilize global average temperatures.[1] According to the data, net-zero commitments have been made by 149 countries, 188 regions, 276 cities, and 1177 companies (representing 88% of global emissions, 93% of global GDP, and 89% of the worldwide population). This indicates substantial progress in climate pledges, although further growth and advancement are still possible.[2] However, achieving net-zero emissions faces many uncertainties. Recent studies have explored key factors affecting net-zero adoption across different sectors, including the availability of natural resources, government debt levels, and political stability.[3] The purpose of the G20, which is composed of 20 major industrial nations (including the G7, BRICS, the EU, Mexico, Argentina, Turkey, Saudi Arabia, South Korea, Indonesia, and Australia), is to promote a more effective achievement of emission reduction targets. To address climate change challenges and promote sustainable development, it is advancing global emission reduction efforts through national climate policy formulation.[4] A "scoreboard" system, as defined by Bloomberg NEF data, is employed by the G20 to assess seven critical areas, specifically the power sector, low-carbon fuels and carbon capture, use and storage, road transport, buildings, industry, circular economy, trade and cross-border emissions. Regarding comprehensive metrics, Europe demonstrates superior performance compared with other regions. France and Germany exhibit the highest scores, followed by the EU average and other major European economies. Japan and South Korea, despite not being OECD countries, exhibit remarkable performance among Asian nations, with overall scores of 58 and 57%, respectively.[5]

In March 2022, Taiwan officially released its "Taiwan's Pathway to Net-Zero Emissions by 2050", which presented a concrete action plan to achieve "net-zero emissions by 2050." The plan is centered on four transformation strategies: "Energy Transformation", "Industrial Transformation", "Lifestyle Transformation", and "Social Transformation." Two fundamental governance pillars are "Technology Research and Development" and "Technological Innovation", which provide guidance for future carbon reduction transformation.[6] The construction industry is responsible for approximately one-quarter of global carbon emissions during construction and operation.[7] Therefore, the International Energy Agency (IEA) suggested that more than 85% of buildings should be prepared for zero-carbon readiness.[8] Consequently, Taiwan has been actively promoting net-zero buildings in recent years to reduce the building sector's environmental impact and achieve carbon neutrality goals. The strategy is based on four main pillars: first, improving energy efficiency in new buildings; second, enhancing energy efficiency in existing buildings; third, increasing appliance energy efficiency; and finally, promoting new technologies and methods for building energy conservation and carbon reduction. Taiwan's pathway to net-zero emissions in 2050 is shown in Fig. 1.[9] These strategies incorporate the concepts proposed by the IEA, the European Union, the United States, and Japan. The implementation of building energy efficiency assessment and labeling systems commenced in 2022, accompanied by the promotion of the establishment of green building
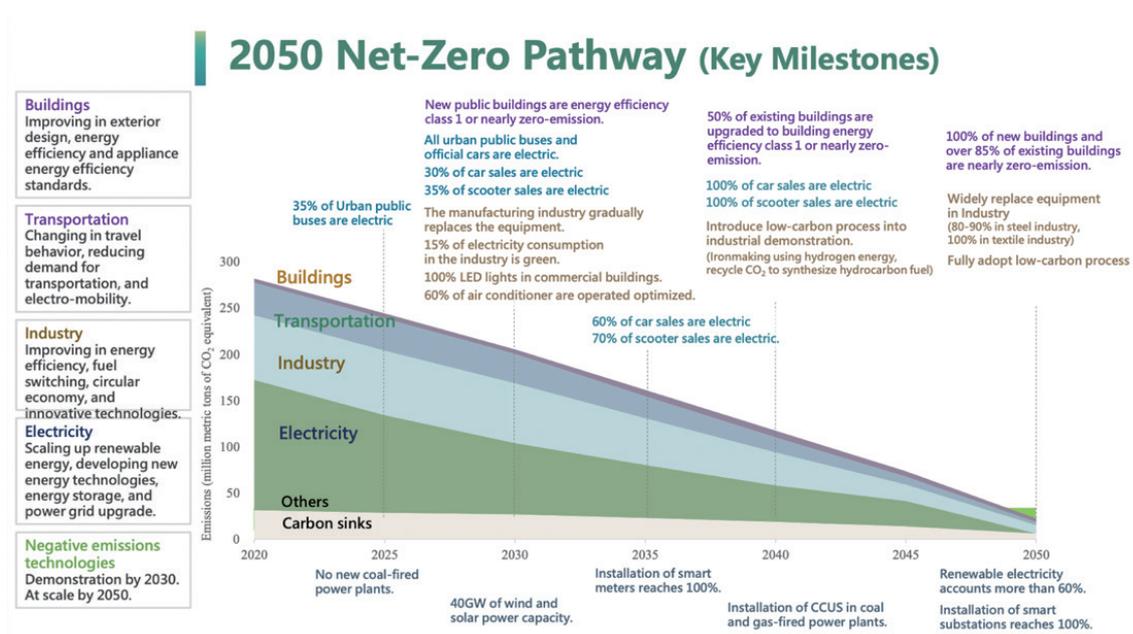
Fig. 1.   (Color online) Taiwan's pathway to net-zero emissions in 2050.[9]

material certification systems.[10] The implementation of these strategies varies according to the type of building in question. For instance, the government primarily employs incentive-based approaches to encourage private existing buildings to undergo energy-saving and carbon-reducing renovations, such as offering rewards or subsidies. In contrast, mandatory measures are adopted for public existing buildings, requiring them to implement relevant energy efficiency improvements and carbon reduction measures.[11]

Carbon emissions associated with the built environment encompass both operational carbon emissions, which refer to the release of carbon dioxide during a building's operational lifespan, and emissions stemming from other stages of the building's lifecycle, such as the production of building materials and the construction phase.[12] It is commonly accepted that the highest levels of carbon emissions are produced during the operational phase of a building, with the majority of these emissions resulting from energy consumption during the building's use.[13] In addition to investigating the potential of innovative materials to reduce carbon emissions during the production and usage of materials, there is a growing emphasis on developing green energy solutions to enhance energy efficiency and reduce high-carbon energy sources.[14] The "Daily Energy Conservation Index" is designed to enhance building energy efficiency and carbon reduction. It is one of the mandatory evaluation indicators for Taiwan's green building certification program, focusing on envelope energy, air-conditioning energy, and lighting energy savings.[15] The importance of a well-designed building envelope in reducing energy consumption and reliance on air-conditioning and heating equipment is well established.[16] Consequently, in this study, the authors place a significant emphasis on the smartification of building envelopes as a priority energy-saving technology.[17]

Automatically adjustable shading glass windows represent an advanced technological solution, which employs three main driving factors: light, heat, and electricity. These windows are capable of automatically adjusting shading effects based on external environmental conditions.[18] Electrochromic glasses (ECGs) represent a promising technological advancement. By applying an electric field to initiate oxidation–reduction reactions, the window color can be reversibly altered to regulate visible light and heat transmittance, thereby controlling the solar radiation entering the building.[19] This technology has significant implications for the development of energy-efficient buildings. A study conducted in Greece demonstrated that, in comparison with clear glass, electrochromic windows resulted in a reduction of approximately 54% in energy consumption over a 25-year period, thereby significantly lowering the building's total energy demand.[20] Moreover, studies conducted in Oman and Saudi Arabia have demonstrated that buildings equipped with ECGs can achieve notable cooling energy efficiency.[21] However, while EC windows show promise in reducing heating, ventilation, and air-conditioning system (HVAC) and lighting energy consumption, their implementation is affected by certain challenges, including relatively low switching speeds and high production costs.[22] Consequently, this research will focus on polymer-dispersed liquid crystal (PDLC) technology, which represents a more cost-effective smart glass solution.[23] PDLC offers significant advantages in the development of net-zero energy buildings. Its numerous benefits include rapid response times, extensive viewing angles, and stability, which address the constraints inherent to conventional liquid crystal displays.[24] The efficiency of building HVAC and lighting systems can be enhanced by ensuring adequate indoor daylight levels, which can offset or reduce the impact of glass on heat loads. In comparison with conventional glass, PDLC windows offer superior thermal control and daylighting performance, with the ability to transition between transparent and translucent states.[25,26] These systems operate without the need for costly polarizers and function effectively across a broad temperature range. The switchable glass systems have been identified as an effective means of reducing building cooling loads and energy consumption, especially in hot climates.[27] Furthermore, studies have demonstrated that when applied to buildings in cold climate zones, this material can contribute to heating energy reduction.[28] Furthermore, the adaptability of polymer and liquid crystal compositions enables the development of customized displays for a wide range of applications, including window glazing and buildings with extensive glass facades.[29] The characterization of large-area PDLC optical properties for architectural applications illustrates optimal performance in light and thermal control.[30] Additionally, PDLC windows can improve visual comfort and daylight distribution within structures while maintaining recommended daylight factor levels.[31] These properties enable buildings with PDLC glass to achieve significant reductions in carbon dioxide emissions and associated cooling costs. White PDLC glass has the greatest potential for savings. Studies have demonstrated that PDLC smart glass in four colors can effectively reduce solar heat gain and air-conditioning costs in comparison with clear glass. White PDLC glass has been shown to exhibit the most significant energy-saving performance in hot-dry climates, reducing solar heat gain by approximately 69% with an air-conditioning cost payback period of 12.1 years.[32] A review of the literature supports the conclusion that the installation of PDLC smart windows in buildings contributes to enhanced energy efficiency and facilitates the transition to net-zero energy buildings.

The development of PDLC technology has transitioned from fundamental material studies to sophisticated system integration involving automated sensing and precision control. In terms of detection, early automation primarily relied on environmental sensors such as light-dependent resistors for ambient illuminance and passive infrared sensors for occupancy detection. Recent innovations have introduced precision sensing for niche applications, such as the use of specialized photodiode circuits to monitor photosynthetically active radiation within the 400–700 nm spectrum to optimize plant growth environments. Parallel to detection advancements, control methodologies have evolved from binary manual switching to wireless Internet of Things (IoT) platforms and high-precision feedback loops. While early IoT controllers allowed for remote operation via smartphone applications and voice commands—despite a negligible network latency of around 2.21 s—the industry has moved toward continuous transmittance regulation. This is achieved through proportional-integral control laws and pulse width modulation drivers, which enable the dynamic tracking of light setpoints and disturbance rejection. Furthermore, commercial scalability has addressed the sizing effects of PDLC films, identifying 0.1 mm as an optimal thickness for balancing optical performance and cost efficiency. As current and apparent power consumptions increase linearly with film area, the integration of step-down transformers and relay modules has become essential for stabilizing large-scale parallel deployments.[33–35] In this research, the authors aim to contribute to global climate change mitigation efforts by examining how smart building envelope technologies, specifically PDLC window films, can improve the indoor built environment and air-conditioning electricity consumption of buildings in Taiwan.

2. Methodology

2.1 Material preparation

In this action of the performance, the smart PDLC film manufactured by BenQ Materials is utilized as the test specimen. When electrically activated in the "ON" status, liquid crystal polymers align in a uniform configuration, allowing light to transmit homogeneously, thereby rendering the PDLC film transparent, similar to clear glass. Conversely, in the "OFF" state without electrical current, liquid crystal polymers assume a random orientation, causing light to scatter multidirectionally, thus producing a translucent, frosted appearance comparable to etched glass. Figure 2 illustrates the mechanism governing light control in smart PDLC films.

In this study, the authors developed an ESP-32S controller that can regulate the activation state of a smart PDLC film using NodeMCU-32S, which is a Lua WiFi IoT development board based on the ESP-32S module, connected to a Woody auxiliary board. This controller enables three control modes through current regulation: activation (ON), deactivation (OFF), or automatic brightness control of the smart PDLC film.
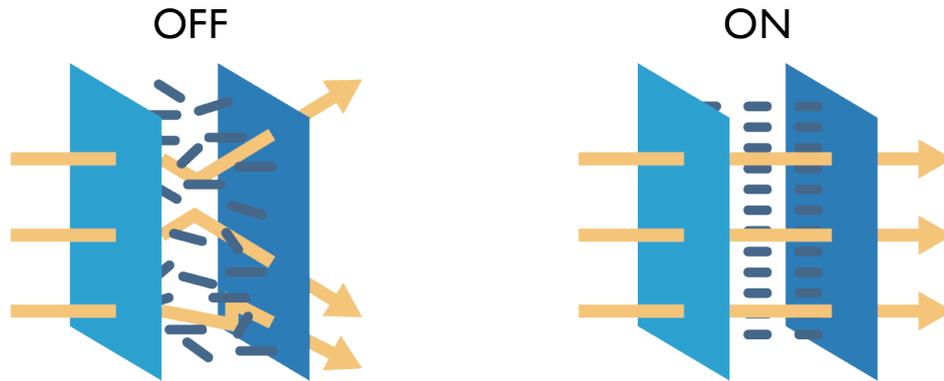
Fig. 2.   (Color online) Illustration of light control mechanism in smart PDLC films.

2.2   Optical and thermal performance testing

In this study, the authors employed a spectrophotometer (HITACHI U-4100) to assess the optical performance of a smart PDLC film adhered on a 6 mm clear glass in accordance with ISO 9050,[36] quantifying transmittance and reflectance. The sample size was 100 mm by 100 mm, and the solar radiation wavelength measurement range was 300 to 2500 nm. The following formulas were used to calculate the visible light transmittance (1), visible light reflectance (2), solar direct transmittance (3), and solar direct reflectance (4) of the samples. Then, in accordance with ISO 10292,[37] FTIR (Thermo Fisher Scientific/Nicolet iS50) was employed to ascertain the surface emissivity of the samples, with measurements obtained within the wavelength range of 2.5 to 25 μm and finally converted to calculate the surface emissivity of the samples.

$$\tau_v = \frac{\sum_{\lambda=380}^{780} \tau(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380}^{780} D_\lambda V(\lambda) \Delta\lambda} \tag{1}$$

$$\rho_v = \frac{\sum_{\lambda=380}^{780} \rho(\lambda) D_\lambda V(\lambda) \Delta\lambda}{\sum_{\lambda=380}^{780} D_\lambda V(\lambda) \Delta\lambda} \tag{2}$$

$$\tau = \frac{\sum_{\lambda=300}^{2500} \tau(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300}^{2500} S_\lambda \Delta\lambda} \tag{3}$$

$$\rho = \frac{\sum_{\lambda=300}^{2500} \rho(\lambda) S_\lambda \Delta\lambda}{\sum_{\lambda=300}^{2500} S_\lambda \Delta\lambda} \tag{4}$$

where τ_v is the light transmittance of the glazing, ρ_v is the light reflectance of the glazing, τ is the solar direct transmittance of the glazing, ρ is the solar direct reflectance of the glazing, $\tau(\lambda)$ is the spectral transmittance of the glazing, $\rho(\lambda)$ is the spectral reflectance of the glazing, D_λ is the relative spectral distribution of illuminant D65, $V(\lambda)$ is the spectral luminous efficiency for photopic vision defining the standard observer for photometry, $\Delta\lambda$ is the wavelength interval, and S_λ is the relative spectral distribution of the solar radiation.

The standard test method for steady-state thermal transmission properties emphasizes the importance of proper calibration and adherence to testing conditions to achieve valid results.[38] The optical properties of the samples are obtained in accordance with the aforementioned steps. Following this, the solar heat gain coefficient (*SHGC*) of the PDLC film glass can be calculated using the formula specified in ISO 9050:

$$SHGC = \tau + \frac{h_i}{h_e + h_i} \times \alpha , \qquad (5)$$

where α is the solar direct absorbance of the glazing, h_e is the heat transfer coefficient towards the outside, $h_e = 23 \ \mathrm{W/m^2K}$, h_i is the heat transfer coefficient towards the inside, $h_e = \left(3.6 + \frac{4.4\dot{\varepsilon}_i}{0.837} \right) \ \mathrm{W/m^2K}$, and ε_i is the corrected emissivity of the inside surface.

The shading coefficient of the smart PDLC film glass, defined as the ratio of the solar gain (due to direct sunlight) passing through the PDLC film glass unit to the solar energy passing through a 3 mm clear float glass, can be obtained by dividing *SHGC* by 0.87.

2.3 Lifetime testing

The authors employed off-on cycling tests, as outlined in GB/T 35847:2018,[39] to evaluate the service life of the smart PDLC film glass. The sample size was 100 mm by 100 mm. Prior to testing, the voltage was modified to ensure it was functioning within the established range. The test was conducted with a 10 s switching cycle (5 s on, 5 s off) for 80000 switching cycles. The visible light transmittance of the smart PDLC film glass was measured both before and after the experiment. The criterion for success was that the change in visible light transmittance before and after the experiment should be at most 3%.

2.4 Accelerated weathering testing

The authors employed an accelerated ageing weathering tester (JOBHO/UL-F21) to assess the weather resistance of the smart PDLC film glass following ASTM G154-16.[40] The sample size was 75 mm by 150 mm. The test conditions were by the specifications outlined in Cycle 1 of Table X2.1, "Some Historical Exposure Conditions", as detailed in ASTM G154-16. The light source comprised UVA-340 ultraviolet lamps, with an 8 h exposure period followed by a 4 h condensation interval during which the lamps were deactivated. The test was conducted for 250 h per cycle, resulting in a total test period of 1200 h.

The evaluation criteria for accelerated ageing weather resistance of optical samples were based on Sect. 7.5, "Acceptance criteria – changes in performance after accelerated weathering", of the BS EN15752-1-2014 standard.[41] This standard specifies the following: The change in visible light transmittance should be less than 0.5, the change in total solar energy transmittance should be below 0.05, and the changes in UV transmittance should be less than 0.03. Regarding surface emissivity change, if the baseline is greater than or equal to 0.2, the change should be less than 0.05; if the baseline is less than 0.2, the change should be less than 0.03.

2.5   Full-scale experiment

In this research, the authors employed a cargo container house at the Guiren Campus of National Cheng Kung University (as shown in Fig. 3) to conduct full-scale experiments investigating the benefits of a smart PDLC film on indoor environments. The experimental setup was primarily designed to evaluate the impact of a smart PDLC film on the indoor environment. Data were collected from multiple sensors measuring various parameters, including temperature, humidity, illuminance, and electricity consumption.

The cargo container house is composed of four abandoned 20-foot standard shipping containers, with overall dimensions of 20 m (length), 10 m (width), and 2.7 m (height), as shown in Figs. 3 and 4. The design concept envisions a residence for two retired elderly occupants. The interior space includes two bedrooms, a living room, a kitchen-dining area, and one bathroom. To enhance the indoor light environment and mitigate the sense of confinement caused by the containers' insufficient height, this house incorporates extensive glazing. The experimental space for this research is the kitchen-dining area. A smart PDLC film, as shown in Fig. 5, was installed on the west-facing windows to investigate its impact on the indoor environment and air-conditioning power consumption.

As illustrated in Fig. 4, the authors installed two thermocouples on two glass panes in west-facing windows to measure the central glass surface temperature for indoor thermal environment

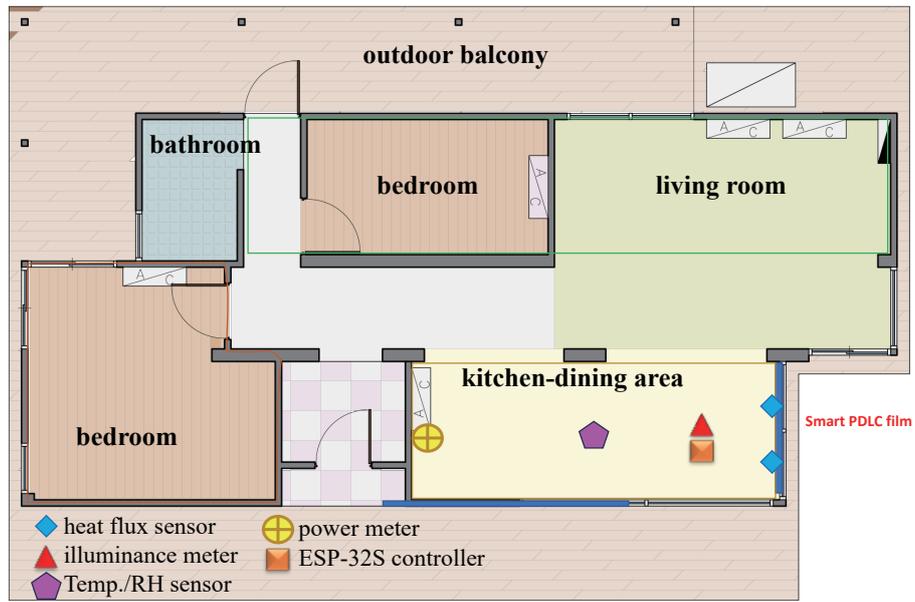Fig. 3.   (Color online) Photograph of cargo container house.

Fig. 4.   (Color online) Indoor space layout and measurement facilities.

(a)

(b)

Fig. 5.   (Color online) Photograph of smart PDLC film in its (a) "on" and (b) "off" states.

measurements. Additionally, a thermometer was installed at the central position of the room at a height of 1.5 m from the floor to measure indoor temperature and humidity.

For indoor light environment measurements, a high-precision digital ambient light intensity sensor module (MAX44009, TAIWANIOT) was installed to measure illuminance at a position 3 m from the window and 1.5 m above the floor. This sensor was connected to the ESP-32S controller, which transmitted the illuminance measurement data to the controller. This configuration enabled the controller to regulate the smart PDLC film state on the basis of real-time illuminance measurements. Furthermore, an LR5000 Utility smart meter was installed in the air-conditioner's distribution panel to measure air-conditioning power consumption.

3. Results and Discussion

3.1 Optical and thermal performance properties of smart PDLC film

Figures 6 and 7 show the transmittance and reflectance spectra of a smart PDLC film in both transparent ("on" state) and shading ("off" state) modes. Table 1 presents the optical and thermal performance properties obtained according to ISO 9050 and ISO 10292 standards.

Experimental results demonstrate that the visible light direct transmittance of the smart PDLC film applied to a 6 mm transparent glass ("on" state) is nearly identical to that of a 6 mm clear glass. However, when the smart PDLC film is in the shading ("off" state), the anisotropic liquid crystal droplets change their alignment orientation, causing visible light scattering. This results in a reduction in visible light (380–780 nm) transmittance to 61.07%, whilst the visible light (380–780 nm) reflectance increases to 13.60%.
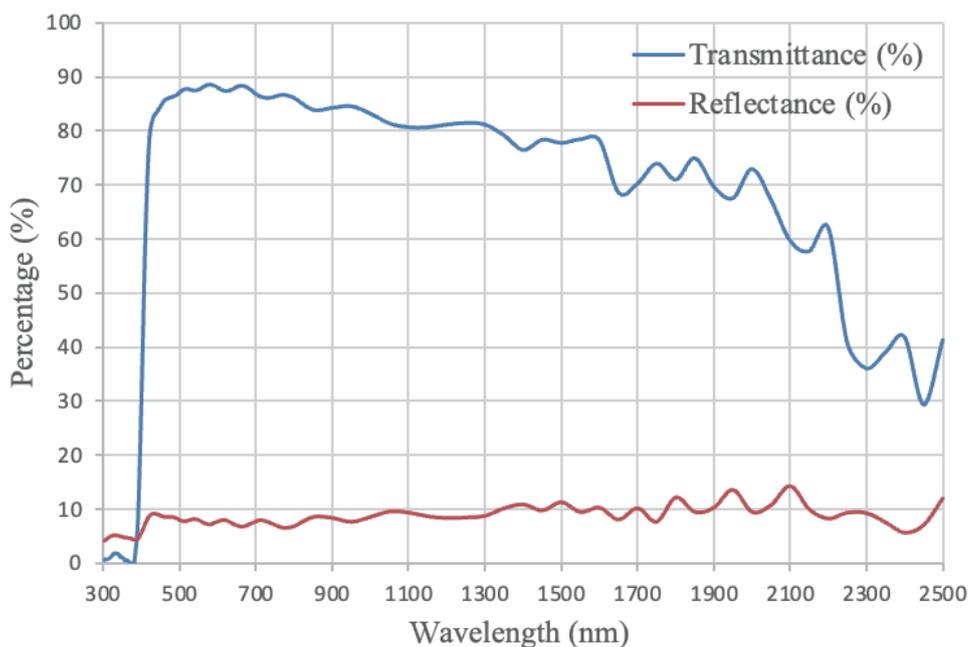

Fig. 6.   (Color online) Solar transmittance and reflectance of smart PDLC film in transparent mode ("on" state).
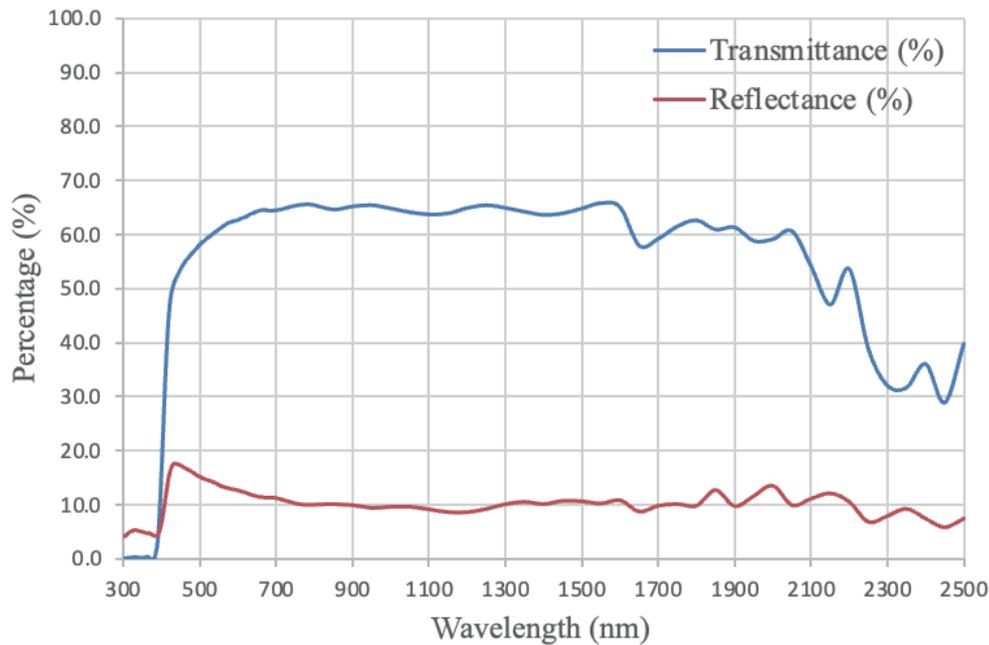
Fig. 7. (Color online) Solar transmittance and reflectance of smart PDLC film in shading mode ("off" state).

Table 1
Optical and thermal properties of smart PDLC film at ON and OFF states.

Item	PDLC film at ON states	PDLC film at OFF states
Visible light transmittance (380–780 nm)	87.68%	61.07%
Visible light reflectance (380–780 nm)	7.71%	13.60%
Solar direct transmittance (300–2500 nm)	79.18%	58.62%
Solar direct reflectance (300–2500 nm)	7.96%	11.31%
SHGC	0.8246	0.6630
Shading coefficient	0.9479	0.7621
Ultraviolet transmittance (300–380 nm)	0.39%	0.00%
Ultraviolet reflectance (300–380 nm)	4.74%	4.81%
Thermal transmittance W/m^2·K	5.821	5.825
Emissivity	Interior: 0.837	Interior: 0.832
	Interior: 0.814	Interior: 0.815

The transmittance and reflectance data in Table 1 indicate that the smart PDLC film in the shading state ("off" state) has less significant effects on ultraviolet (300–380 nm) and near-infrared (780–2500 nm) transmittances than on visible light transmittance. When the smart PDLC film transitions from the transparent state to the shading state, the ultraviolet transmittance decreases from 0.39 to 0.00%, whilst the ultraviolet reflectance increases from 4.74 to 4.81%.

Consequently, the overall solar radiation (300–2500 nm) transmittance of the smart PDLC film decreases from 79.18 to 58.62%, whilst the reflectance increases from 7.96 to 11.31%. When

the smart PDLC film transitions from the transparent state to the shading state, *SHGC* decreases from 0.8246 to 0.6630, demonstrating that the smart PDLC film can decrease solar radiation entering the interior by 16.16%.

The thermal transmittance (U-value) of the smart PDLC film exhibited minimal variation between the ON and OFF states, measuring 5.821 and 5.825 W/m^2·K, respectively. This negligible difference of 0.07% indicates that the electrooptical switching mechanism does not significantly affect the film's thermal insulation performance. Whilst the PDLC technology effectively modulates visible light transmittance (87.68% in the ON state versus 61.07% in the OFF state), it provides limited thermal resistance compared with conventional insulated glazing systems.

The stable thermal transmittance across both operational states can be attributed to the polymer-liquid crystal composite structure maintaining constant thermal conductivity regardless of molecular orientation. The liquid crystal droplets dispersed within the polymer matrix undergo reorientation upon voltage application, affecting optical properties through refractive index matching; however, this molecular realignment does not alter the material's bulk thermal transport characteristics. Consequently, heat transfer through conduction and convection mechanisms remains essentially unchanged between the two switching states.

The interior emissivity values demonstrated comparable stability, measuring 0.837 and 0.832 for the ON and OFF states, respectively. These results further confirm minimal variations in thermal radiative properties during electrooptical switching, suggesting that the surface characteristics governing long-wave infrared radiation remain unaffected by the applied electric field.

For building energy efficiency applications, these findings indicate that PDLC smart windows should be integrated with low-emissivity coatings or incorporated into multiple glazing configurations to achieve adequate thermal performance whilst maintaining dynamic solar control capabilities. The combination of switchable visible light transmission and enhanced thermal insulation would optimize both visual comfort and energy conservation in smart building façade systems.

3.2   Lifetime testing

According to the GB/T 35847 standard, two 4 mm clear float glass specimens with smart PDLC films were tested for visible light transmittance in their ON state after 8000 switching cycles. The measured transmittance values were 87.68 and 87.39%, showing a difference of 0.29%.

The minimal difference of 0.29% in visible light transmittance between the two specimens falls well within the standard's requirement that the variation should not exceed 3% in the ON state. This high consistency in optical performance after extensive cycling (8000 switches) demonstrates the reliability and stability of the smart PDLC film when applied to clear float glass. The results suggest that the smart PDLC film maintains its optical switching properties without significant degradation under repeated electrical activation, meeting the durability requirements specified in GB/T 35847.

3.3 Accelerated weathering test analysis

The optical properties of smart PDLC specimens were evaluated following 1200 h of QUV accelerated weathering test exposure. Measurements were conducted according to glass optical property standards (ISO 9050, 10292), comparing the optical characteristics before and after accelerated weathering testing. The comparative results are presented in Fig. 8.

The weathering test results were assessed against the acceptance criteria specified in BS EN15752-1-2014 Section 7.5 (Changes in performance after accelerated weathering). Table 2 shows the key findings.

All measured parameters demonstrated remarkable stability, falling well within the acceptance criteria thresholds. The change in visible light transmittance was minimal at 0.0067, significantly below the 0.05 limit. Similarly, *SHGC* showed a minor variation of 0.0049, while UV transmittance remained unchanged. The emissivity change was recorded at 0.01, meeting both high and low emissivity material standards.
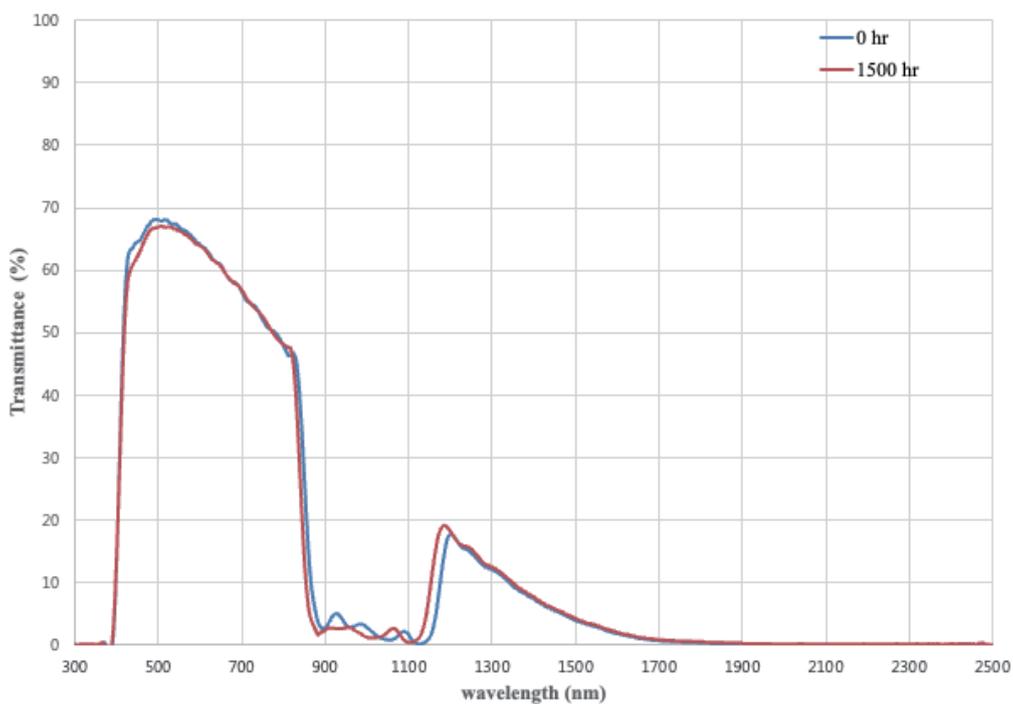

Fig. 8.   (Color online) Solar transmittance of smart PDLC film before and after accelerated weathering testing.

Table 2
Changes in optical properties after accelerated weathering testing.

Acceptance criterion	Test result
Change in visible light transmittance < 0.05	0.0067
Change in *SHGC* < 0.05	0.0049
Change in UV transmittance < 0.03	0
Change in emissivity < 0.05 (for emissivity ≥ 0.2) or < 0.03 (for emissivity < 0.2)	0.01

To contextualize these results for real-world applications, the authors analyzed the test conditions relative to Taiwan's geographical location near the Tropic of Cancer. The region's solar exposure characteristics are as follows.

- Annual average sunshine duration: 2000 h
- Daily average solar radiation: 4.2–5.0 kWh/m^2/day
- Average annual global horizontal irradiance (GHI): 2000 kWh/m^2

The laboratory testing utilized UVA radiation equipment with an energy output of 0.2844 MJ/m^2-h, representing 1.2341% of total solar radiation energy. On the basis of these parameters, the authors determined that Taiwan's maximum annual UVA (300–365 nm) exposure equivalence corresponds to 219 h of accelerated UVA weathering test time.

The specimens successfully completed 1200 h of QUV accelerated weathering testing, which translates to approximately 5 years of outdoor exposure under Taiwan's climatic conditions. This result indicates that smart PDLC specimens can maintain stable optical properties for a minimum weathering period of five years.

These findings are particularly significant for architectural applications where the long-term stability of optical properties is essential. The minimal changes observed across all measured parameters demonstrate the robustness of the smart PDLC technology and its suitability for practical applications requiring sustained performance under environmental exposure.

3.4　Impact of smart PDLC film on indoor light environment

Figure 9 illustrates the illuminance data for the smart switchable film in both the "on" and "off" states. Measurement results demonstrate that when the switchable film is in its transparent
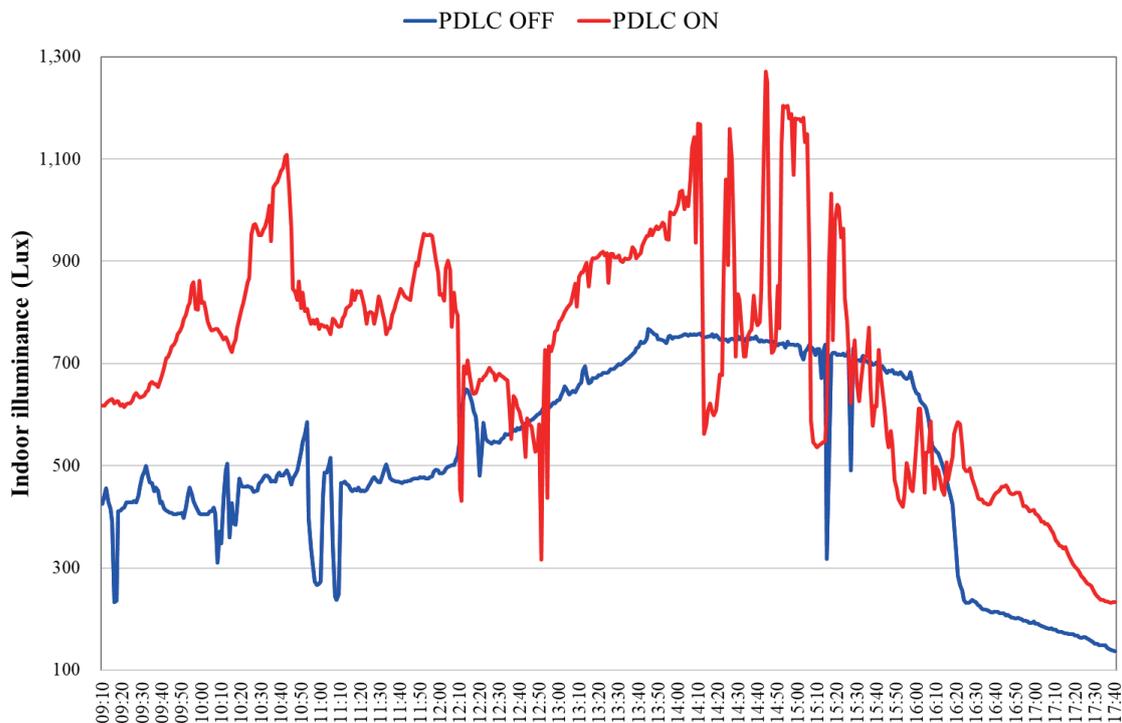

Fig. 9.　(Color online) Effects of PDLC film states on indoor daylighting environment.

state ("on"), the average illuminance measured on indoor desktop surfaces attains 700 Lux, with maximum values exceeding 1000 Lux. Conversely, when the switchable film is in its deactivated state ("off"), it transforms direct light into diffused light entering the interior space, thereby reducing the average desktop illuminance to 500 Lux, with maximum values not exceeding 800 Lux.

This observed phenomenon can be explained by the fundamental optical properties of the smart PDLC material. In the "on" state, the liquid crystal molecules align uniformly under electrical stimulation, creating a homogeneous medium that allows direct light transmission with minimal scattering. This alignment effectively permits the full spectrum of incident light to penetrate the film unimpeded, resulting in higher illuminance values within the interior space. The substantial maximum values exceeding 1000 Lux indicate areas directly exposed to unobstructed sunlight penetration.

In contrast, the "off" state represents a significant alteration in the film's optical behavior. Without electrical current, the liquid crystal molecules revert to random orientations, creating numerous interfaces within the material that scatter incoming light. This scattering mechanism effectively converts directional light rays into multidirectional diffused light, distributing illuminance more evenly throughout the space whilst reducing the overall light transmission efficiency. The measured reduction values of approximately 29% in average illuminance (from 700 to 500 Lux) and 20% in maximum illuminance (from 1000+ to 800 Lux) quantify the film's light-modulating capability, which has significant implications for both energy management and visual comfort in architectural applications.

3.5 Impact of smart PDLC film on indoor thermal environment

Figure 10 presents the comparative measurement results of glass surface and indoor temperatures throughout the day under two modes of the smart PDLC film: transparent ("on") and shading ("off"). The measurements reveal that when the smart PDLC film is in its transparent state ("on"), solar radiation energy directly penetrates the glass and enters the interior space, causing the indoor temperature in the perimeter zone near the window to fluctuate in real time with outdoor temperature variations.

When the smart PDLC film is in its shading state ("off"), both the glass surface and indoor temperatures in the perimeter zone demonstrate a delayed response relative to outdoor temperature changes. This phenomenon can be attributed to the reduction in daylight transmittance in the shading state ("off") at 58.62% compared with the transparent state ("on") at 79.18%—a decrease of 20.56%. Additionally, the daylight reflectance increases by 3.35% (from 7.96% in the "on" state to 11.31% in the "off" state), resulting in a significant reduction in direct radiative heat transfer to the interior space.

The measurements quantify the film's thermal modulation capability, demonstrating how the electrooptical properties of the smart PDLC film can be leveraged to control not only light transmission but also thermal energy flow through building envelopes. This dual functionality presents substantial implications for building energy efficiency, particularly in climates with high solar heat gain potential. The delayed thermal response in the "off" state indicates the
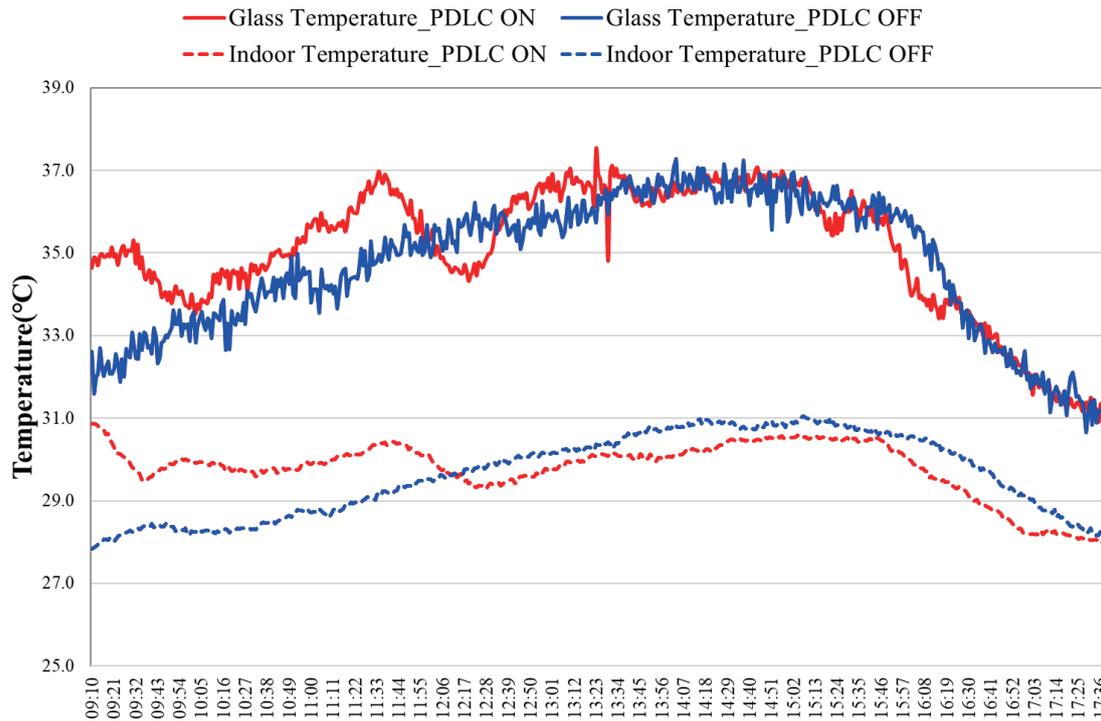
Fig. 10.   (Color online) Effects of PDLC film states on indoor thermal environment.

film's capacity to act as a dynamic thermal buffer, potentially reducing cooling loads during peak outdoor temperature periods and contributing to more stable indoor thermal conditions.

3.6   Energy-saving effect of smart PDLC film

Figure 11 presents a comparison of air-conditioning power consumption under the transparent ("on") and shading ("off") states of the switchable film, using data from two days with similar outdoor temperatures. Experimental results reveal that when the switchable film is in its transparent state ("on"), the air-conditioning system operates at full load after 10:00. In contrast, when the film is in its shading state ("off"), the west-facing installation blocks a greater proportion of solar radiation heat from entering the interior during afternoon hours, resulting in the partial load operation of the air-conditioning system during this period.

Consequently, the daily energy consumption of the air-conditioning system with the switchable film in the shading state ("off") demonstrates a 5% reduction compared with when the film is in the transparent state ("on"). This quantifiable energy efficiency benefit can be attributed to the film's capability to modulate solar heat gain through the building envelope, particularly during peak solar radiation periods.

The observed energy savings validate the thermal performance advantages of the PDLC technology in building applications. By strategically controlling the film's state based on solar orientation and time of day, significant reductions in cooling loads can be achieved. The west-
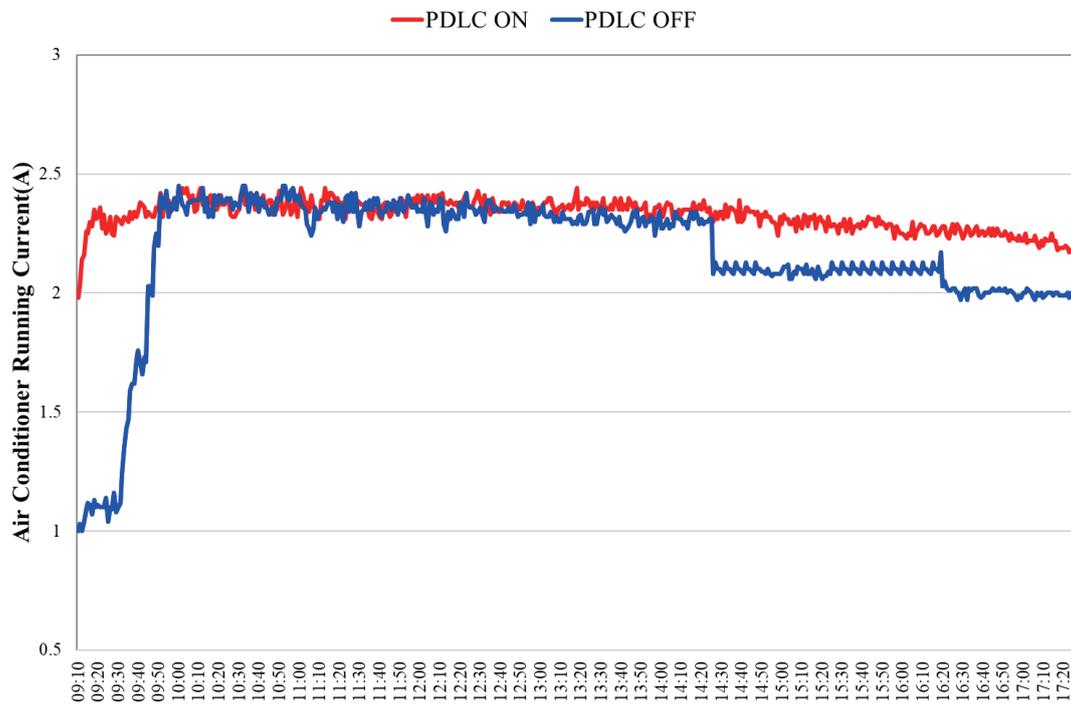
Fig. 11.　(Color online) Effects of PDLC film states on electricity consumption of air-conditioning system.

facing installation provides particular benefits during afternoon hours when solar altitude and intensity typically contribute to peak cooling demands in buildings.

These findings suggest that integrating smart PDLC film technology into building management strategies offers tangible energy efficiency improvements whilst maintaining the flexibility to optimize visual comfort through the dynamic control of transparency. The 5% energy reduction represents a meaningful contribution to overall building energy performance, particularly when considered across the cooling season or in buildings with substantial glazed areas.

3.7　Occupant-centric control technology applied to smart switchable film for indoor light environment impact

On the basis of illuminance experimental results under different modes, the authors proposed an automatic mode system for the smart PDLC film utilizing occupant-centric control technology, as illustrated in Fig. 12. The automatic control logic for the smart PDLC film in this study employs the average illuminance values of 500 Lux in the shading state ("off") and 700 Lux in the transparent state ("on") as the control parameters.

In automatic mode, the system regulates solar radiation entering the interior by adjusting the input current to the smart PDLC film according to measurements from light sensors. The system employs a strategic buffer zone (500–700 Lux) to prevent frequent state changes. When illuminance values fall within this range, the system maintains its current state, reducing
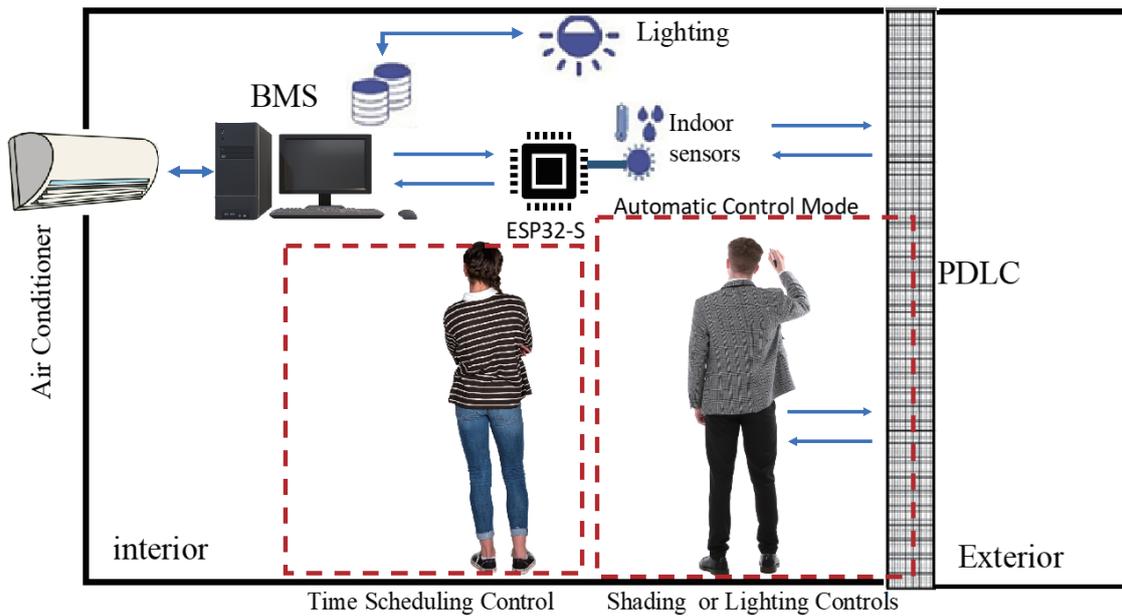
Fig. 12.   (Color online) Occupant-centric control logic of the smart PDLC film.

unnecessary cycling and enhancing user comfort. This hysteresis approach represents an important consideration in user experience design, as frequent transitions between states can potentially cause visual discomfort and distraction. When illuminance exceeds 700 Lux, the smart PDLC film transitions to the deactivated state ("off"), enabling the film to block maximum solar incidence. Conversely, when illuminance falls below 500 Lux, the PDLC film activates to its transparent state ("on"), maximizing solar radiation entry into the interior space.

For hardware development, an ESP32-S development board was employed, programmed with 86Duino code to implement the control logic. The system allows switching between three operational modes: manual transparent state ("on"), manual deactivated state ("off"), and automatic mode.

Figure 13 presents the indoor light environment measurement data when the smart PDLC film operates in automatic mode with occupant-centric control technology. Experimental results demonstrate that under automatic mode, the average desktop illuminance throughout the day measures 600 Lux, which falls between the average illuminance values of 700 Lux in the activated mode ("on") and 500 Lux in the deactivated mode ("off").

In automatic mode, the smart PDLC film adjusts automatically according to brightness levels. When illuminance exceeds 700 Lux, the smart switchable film transitions to the deactivated state ("off") to reduce illuminance. When illuminance falls below 500 Lux, the film switches to the activated mode ("on") to provide sufficient light. To address frequent activation-deactivation cycles, the system maintains its current state when illuminance remains within the 500–700 Lux range. For example, if the film is in an activated state, it remains activated within this illuminance range. However, experiments revealed that during afternoon periods of excessive brightness, even the automatic deactivation of the optical properties could not effectively reduce illuminance levels.
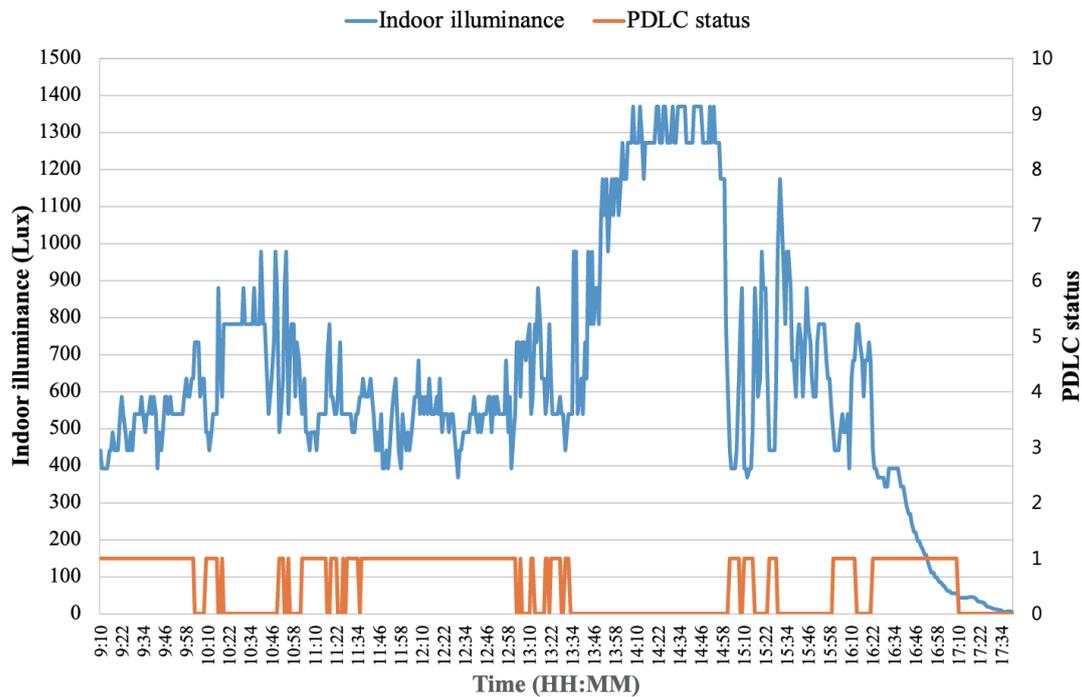
Fig. 13.　(Color online) Smart PDLC film for indoor light environment impact.

3.8　Building energy performance evaluation of PDLC smart window film

3.8.1　Simulation setup and baseline energy consumption

The energy performance evaluation was conducted using the Building Energy Simulation and Technology Analysis Integration (BESTAI) platform, a web-based simulation tool specifically developed for Taiwan's built environment. The simulated subject was a cargo container house described in Sect. 2.6. The building envelope characteristics included a roof thermal transmittance (U-value) of 1.0 W/m^2·K, an external wall U-value of 2.0 W/m^2·K, and a window U-value of 6.16 W/m^2·K. The window-to-wall ratios varied across different orientations: 0.65 for the west façade, 0.30 for the east façade, 0.85 for the south façade, and 0.31 for the north façade. The glazing system exhibited an *SHGC* of 0.3977 and a visible light transmittance of 0.4437.

The internal loads comprised two occupants with one visitor per hour, 21 recessed luminaires (15 W each), and 4 shelf lights (23.7 W each), totaling 409.8 W of installed lighting capacity. The HVAC system consisted of five small split-type air-conditioning units: four units with a cooling capacity of 2.2 kW and an energy efficiency ratio (*EER*) of 4.3, and one unit with a cooling capacity of 2.3 kW and an *EER* of 3.95. The operational schedule was set for weekdays from 9:30 to 17:30, with the thermostat set point maintained at 26 °C during occupied hours.

Under the baseline scenario without any energy-saving control strategies, the annual electricity consumption was simulated to be 1762 kWh. Table 3 presents the monthly electricity consumption breakdown, demonstrating typical seasonal variation patterns with higher

Table 3
Monthly electricity consumption of container building without energy-saving control (kWh).

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior lighting	77	70	77	77	73	77	80	73	77	77	73	80	911
Air-conditioning	13	28	17	42	80	130	118	113	126	84	52	28	831
Fans	0	1	0	1	2	3	3	3	3	2	1	1	20
Total	90	99	94	120	155	210	201	189	206	163	126	109	1762

consumption during summer months due to increased cooling loads and reduced consumption during winter months.

3.8.2   Impact of occupancy-based lighting control

The implementation of occupancy-based lighting control systems resulted in substantial energy savings. As shown in Table 4, the annual electricity consumption decreased to 1145 kWh, representing a 35% reduction (617 kWh) compared with the baseline scenario. This significant reduction was primarily attributed to the elimination of unnecessary lighting operation during unoccupied periods and the optimization of lighting schedules based on actual occupancy patterns.

The monthly consumption data revealed consistent savings throughout the year, with the lighting component showing marked reduction across all months. This finding indicates that occupancy-sensing technologies can achieve substantial lighting energy savings in buildings with distinct occupied and unoccupied periods. The 35% savings observed in this study reflect the relatively simple occupancy pattern of the container building with clearly defined working hours.

3.8.3   Combined effects of lighting control and high-efficiency HVAC

The synergistic implementation of occupancy-based lighting control and high-efficiency air-conditioning systems yielded cumulative energy savings. Table 5 demonstrates that the combined strategy reduced annual electricity consumption to 886 kWh, achieving a 50% reduction (876 kWh) relative to the baseline. Isolating the contribution of high-efficiency HVAC systems alone indicates independent savings of approximately 15% (259 kWh annually).

The relatively modest independent contribution of HVAC efficiency improvement (15%) compared with lighting control (35%) can be attributed to two primary factors. First, the baseline HVAC system already featured reasonably efficient equipment with *EER* values ranging from 3.95 to 4.3, limiting the potential for marked efficiency gains. Second, the reduced internal heat gains from efficient lighting systems contributed to decreased cooling loads, creating a beneficial interaction effect. This lighting–HVAC interaction demonstrates that lighting energy savings typically yield additional indirect savings through reduced cooling requirements, particularly in cooling-dominated climates such as Taiwan.

Table 4
Monthly electricity consumption with occupancy-based lighting control (kWh).

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior lighting	31	28	31	31	29	31	32	29	31	31	29	32	365
Air-conditioning	11	24	13	36	73	122	110	106	119	77	46	23	760
Fans	0	1	0	1	2	3	3	3	3	2	1	1	20
Total	42	53	44	68	104	156	145	138	153	110	76	56	1145

Table 5
Monthly electricity consumption with lighting control and high-efficiency HVAC (kWh).

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior lighting	31	28	31	31	29	31	32	29	31	31	29	32	365
Air-conditioning	7	16	9	24	48	81	73	70	78	50	30	15	501
Fans	0	1	0	1	2	3	3	3	3	2	1	1	20
Total	38	45	40	56	79	115	108	102	112	83	60	48	886

3.8.4   Integration of smart PDLC window film technology

The addition of smart PDLC window film technology to the comprehensive energy management strategy produced additional energy savings while addressing multiple performance criteria. As presented in Table 6, the integration of all three technologies—occupancy-based lighting control, high-efficiency HVAC systems, and smart PDLC window film—resulted in a total annual electricity consumption of 845 kWh, representing a 52% reduction (917 kWh) compared with the baseline scenario. The isolated contribution of the PDLC window film amounted to approximately 2% additional savings (41 kWh annually) when combined with other control strategies.

PDLC technology operates through voltage-controlled switching between the transparent and translucent states, offering dynamic control over solar heat gain and visible light transmission. In the transparent state (voltage applied), liquid crystal molecules align to permit high visible light transmittance while maintaining moderate solar control. In the translucent state (voltage removed), the random orientation of liquid crystal droplets scatters incoming light, providing privacy and enhanced solar heat rejection. This switchable characteristic distinguishes PDLC films from conventional static glazing systems and complementary technologies such as electrochromic glazing, which modulates optical properties through gradual tinting rather than discrete state switching.

The 2% energy savings contribution observed in this study, while appearing modest in isolation, warrants careful interpretation within the context of the comprehensive control strategy. Several factors affected the measured performance of the PDLC window film, as follows:
• The west-facing orientation of the primary façade presents challenging solar control conditions, particularly during afternoon hours when solar heat gains peak. The existing baseline glazing already featured a relatively low *SHGC* (0.3977), establishing a moderately efficient starting point that limited the incremental improvement potential.

Table 6
Monthly electricity consumption with all three technologies integrated (kWh).

Category	Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	Total
Interior lighting	28	26	28	28	27	28	29	27	28	28	27	29	333
Air-conditioning	7	15	8	23	47	80	72	69	77	50	30	14	492
Fans	0	1	0	1	2	3	3	3	3	2	1	1	20
Total	35	42	36	52	76	111	104	99	108	80	58	44	845

- The substantial reduction in internal heat gains achieved through efficient lighting and optimized HVAC operation diminished the relative contribution of envelope-based solar control to overall building energy performance.
- The control algorithm employed in this simulation utilized the basic switching logic based on solar radiation intensity. More sophisticated predictive control strategies incorporating weather forecasts, occupancy patterns, and thermal comfort optimization can potentially enhance energy savings.
- The compact building size ($72 \ m^2$ floor area) and limited total window area constrained the absolute magnitude of envelope-related energy impact, regardless of glazing system performance.

Despite these factors, field studies of PDLC installations in diverse building types have documented energy savings ranging from 3 to 15% depending on the climate zone, building orientation, window-to-wall ratio, and control strategy sophistication. The performance observed in this cargo container house simulation aligns with the lower end of this range, consistent with the presence of complementary energy efficiency measures that address alternative savings pathways.

3.8.5 Comparative analysis and critical role of smart PDLC technology

Table 7 shows the comparative performance of all investigated strategies, revealing a clear hierarchy of direct energy-saving effectiveness. However, the strategic importance of smart PDLC window film technology extends substantially beyond the singular metric of annual energy consumption reduction, particularly within Taiwan's subtropical climate context and evolving building performance requirements.

The strategic significance of smart PDLC window film technology in Taiwan's building sector derives from multiple critical factors that transcend direct energy savings metrics, as follows:

Multidimensional Performance Benefits

PDLC technology simultaneously addresses thermal comfort, visual comfort, and privacy control—three performance dimensions that conventional static glazing cannot optimize concurrently. In Taiwan's subtropical climate characterized by intense solar radiation and high ambient temperatures, the ability to dynamically modulate both solar heat gain and glare conditions enables substantial improvements in occupant comfort and productivity. The switchable privacy control feature provides additional functional benefits that are particularly

Table 7
Energy performance of all control strategies.

Control strategy	Annual energy consumption (kWh)	Energy savings (kWh)	Percentage reduction (%)
Baseline (no controls)	1762	—	—
Occupancy-based lighting	1145	617	35
Lighting + High-efficiency HVAC	886	876	50
All technologies combined	845	917	52

valued in commercial and residential applications, eliminating the need for conventional window treatments while maintaining view access.

Peak Demand Reduction Potential

While annual energy consumption provides one performance metric, peak electrical demand reduction represents an equally critical consideration for grid stability and utility cost management. PDLC window films can effectively reduce peak cooling loads during afternoon hours when solar heat gains and air-conditioning demand coincide. In Taiwan's electricity rate structure, which incorporates significant demand charges for commercial customers, peak load reduction can generate economic benefits comparable to or exceeding those derived from total energy savings. This characteristic positions PDLC technology as a valuable component of demand response strategies and building-grid integration initiatives.

Retrofit Applicability and Installation Flexibility

Unlike many envelope improvement strategies that require complete window replacement, PDLC film technology can be retrofitted to existing glazing through surface application. This characteristic offers substantial advantages for Taiwan's existing building stock, where wholesale façade replacement is often economically prohibitive or architecturally constrained. The relatively straightforward installation process, minimal structural requirements, and compatibility with diverse glazing configurations enhance the practical viability of widespread deployment across commercial, institutional, and residential building sectors.

Integration with Building Automation and IoT Ecosystems

Smart PDLC window films operate through low-voltage electrical control systems that readily interface with building automation systems and IoT platforms. This integration capability enables sophisticated control strategies incorporating multiple input parameters: solar radiation sensors, occupancy detection, thermal comfort indices, glare probability assessments, and weather forecasts. Machine learning algorithms can optimize PDLC switching schedules based on historical performance data and predicted conditions, potentially enhancing energy savings substantially beyond the baseline performance observed in this study. Furthermore, integration with demand response programs allows utility-directed control during peak demand events, supporting grid stability while reducing electricity costs.

Climate Change Adaptation and Resilience

Climate projections for Taiwan indicate the increasing frequency and intensity of extreme heat events, with mean summer temperatures expected to rise 1.3–1.8 °C by 2050 under moderate emission scenarios.[42] Dynamic glazing technologies such as PDLC films offer adaptive capacity to manage escalating cooling loads while maintaining an acceptable indoor

environmental quality. The ability to respond to transient extreme conditions through real-time switching provides resilience advantages that static building envelopes cannot achieve. This adaptive characteristic positions PDLC technology as a forward-looking investment aligned with long-term climate adaptation strategies.

Synergistic Effects in Comprehensive Building Retrofits

The simulation results demonstrate that PDLC window film technology achieves optimal performance when implemented as a component of comprehensive building energy management strategies rather than as an isolated intervention. The 2% incremental savings observed when combined with lighting and HVAC controls may underestimate the technology's potential in buildings lacking such complementary systems. In existing buildings with inefficient lighting, oversized HVAC equipment, or poor envelope performance, PDLC films can deliver more substantial energy reductions by addressing otherwise dominant solar heat gain contributions. This scalability across diverse building conditions and performance baselines enhances the technology's versatility and applicability.

Translating the observed energy savings to environmental and economic impacts provides additional context for evaluating technology deployment. The 41 kWh annual savings attributable to the PDLC window film, while modest in absolute terms for this 72 m^2 building, corresponds to approximately 21 kg CO_2e annually based on Taiwan's grid emission factor of 0.509 kg CO_2e/kWh. Scaled to Taiwan's total commercial building floor area of approximately 280 million m^2, the widespread adoption of PDLC technology achieving similar performance would yield aggregate annual emission reductions of approximately 82000 tonnes CO_2e— equivalent to removing 17000 passenger vehicles from service annually. This calculation illustrates how technologies with modest per-building impacts can generate significant sector-level benefits through widespread deployment.

The economic analysis of PDLC window film deployment requires the consideration of installation costs, energy cost savings, demand charge reductions, and non-energy benefits. Current market prices for PDLC film systems range from $260 to 485 USD per square meter installed, depending on film specifications, project size, and control system complexity. For the container building investigated in this study (approximately 32 m^2 of glazed area), the total installation cost would range from $8300 to 15500 USD. Based solely on energy savings at Taiwan's average commercial electricity rate of $0.11 USD/kWh, simple payback periods would exceed 30–60 years—economically unfavorable for most building owners. However, this narrow financial perspective excludes several important considerations:

- Demand charge savings, which typically constitute 30-40% of commercial electricity bills, can reduce payback periods by 25–35% when peak load reductions are properly valued.
- Avoided costs of alternative comfort improvement measures (such as motorized shading systems, privacy films, or supplementary air-conditioning capacity) should be credited against PDLC installation costs.
- Productivity improvements associated with enhanced thermal and visual comfort can generate economic benefits substantially exceeding direct energy savings, particularly in knowledge-intensive workplaces where personnel costs dominate operational expenses.
- Market differentiation and tenant attraction benefits in commercial real estate markets increasingly value advanced building technologies and sustainable features.

When these broader considerations are incorporated into life-cycle cost analysis, PDLC window film technology can achieve competitive economic performance, particularly in high-value commercial applications where occupant comfort and building performance differentiation drive decision-making.

From a policy perspective, the findings of this study suggest several implications for Taiwan's building energy efficiency programs and green building certification systems. First, performance-based evaluation frameworks should recognize the multi-dimensional benefits of smart window technologies beyond simple energy consumption metrics. Credit structures in Taiwan's Ecology, Energy Saving, Waste Reduction, and Health green building rating system can be enhanced to properly value dynamic envelope technologies that provide adaptive capacity, peak demand reduction, and resilience benefits. Second, financial incentive programs targeting building retrofits should consider technology-specific subsidies or favorable financing mechanisms for smart window installations, particularly in existing buildings where envelope improvements are otherwise cost-prohibitive. Third, demonstration projects and performance monitoring initiatives can reduce market barriers by documenting actual performance under Taiwan's climate conditions and building operational patterns, addressing information gaps that currently inhibit wider adoption.

The simulation demonstrates that smart PDLC window film technology, while contributing modestly to direct energy savings when combined with comprehensive efficiency measures, serves as a critical enabling technology for achieving high-performance building operations in Taiwan's challenging subtropical climate. Its strategic importance derives not from energy savings alone, but from the confluence of thermal comfort enhancement, visual environment optimization, retrofit applicability, integration capability with advanced building controls, climate adaptation potential, and economic viability when comprehensively evaluated. As Taiwan advances toward its net-zero carbon targets and confronts intensifying climate change impacts, technologies that provide adaptive capacity and multidimensional performance benefits such as smart PDLC window films will assume increasing importance in the building sector's transformation trajectory.

4. Conclusions

In this study, the authors comprehensively evaluated smart PDLC window film technology through laboratory characterization, durability testing, full-scale experimentation, and building energy simulation. Laboratory measurements demonstrated dynamic optical control with visible light transmittance varying from 87.68% (transparent state) to 61.07% (shading state) and *SHGC* decreasing from 0.8246 to 0.6630, achieving 16.16% solar heat gain reduction. Durability assessments validated stable performance after 8000 switching cycles and accelerated weathering equivalent to 5 years under Taiwan's climate conditions.

Full-scale experimental measurements confirmed a 5% reduction in air-conditioning energy consumption in the shading state while effectively modulating indoor illuminance between 500 and 700 Lux. The occupant-centric control system with illuminance-based hysteresis logic successfully maintained optimal indoor light levels without frequent state transitions. Building

energy simulations revealed that the integration of PDLC technology with occupancy-based lighting control and high-efficiency HVAC systems achieved a cumulative 52% energy reduction compared with baseline conditions, with PDLC contributing additional 2% savings (41 kWh annually) beyond other efficiency measures.

The strategic value of smart PDLC technology extends beyond direct energy savings to include simultaneous thermal comfort optimization, glare control, dynamic privacy, and peak demand reduction. The retrofit applicability through surface application enables cost-effective envelope improvements in existing buildings without window replacement. Integration capability with building automation systems positions PDLC for enhanced performance through advanced control strategies. These findings demonstrate that the smart PDLC window film represents a viable multifunctional solution for building envelope enhancement, contributing to Taiwan's net-zero emissions pathway while improving occupant comfort. Future research should explore advanced control algorithms, performance optimization across diverse climate zones, and life-cycle environmental impacts to further enhance the technology's contribution to sustainable built environments.

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