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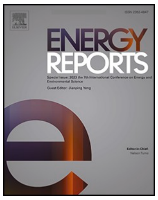

Assessing energy savings and visual comfort with PDLC-based smart window in an Istanbul office building: A case study

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ABSTRACT

Lighting applications in architectural structures have a high share in energy consumption. Inefficient lighting applications and technologies will increase energy consumption and do not guarantee the visual comfort desired by users. Recognizing the importance of user comfort, this study takes a deeply user-centric approach in proposing feasible lighting control methods that can improve energy efficiency in smart and carbon-neutral future buildings and change daylight's benefits in favor of the user. Smart glass technology, which can adjust the color and transmittance of the light in response to external stimuli (applied voltage) and can be dynamically modulated, changing window and door characteristics, has high potential in the market for modern societies. This paper develops an innovative lighting control method to improve energy efficiency and visual comfort and reduce energy consumption. The daily performance of the proposed control methods regarding illuminance, uniformity factor, and energy consumption is experimentally analyzed in a test bench modeling an office environment with IG80 glass (for comparison), artificial lighting source (LED lamp), and polymer-dispersed liquid-crystal (PDLC)-based smart window. The research methodology involved a detailed analysis of the relationship between performance metrics and dimmer percentages and comparing the energy consumption performance of the lighting methods with other design parameters and technological advances. This algorithm prioritizes user comfort and considers the PDLC-based smart window light transmittance and LED lamp dimmer control depending on daylight. The results show that the proposed algorithm can increase energy savings by up to 22 %. While efficient lighting control is closely related to weather conditions and indoor specifications, it has similar energy consumption performance compared to research into design parameters and technological advances, eliminating further efforts.

1. Introduction

Smart glass with adjustable light transmittance, which can reduce costs and energy use depending on various lighting factors, is critical in the energy-efficient buildings of the future (Gago et al., 2015; Tällberg et al., 2019). In addition to the energy advantage, it is predicted by (Allen et al., 2017) that it will not compromise on lighting comfort. Smart glass applications fall mainly into four categories: suspended particle, liquid crystal, thermotropic, and electrochromic (EC). The common feature of each type is that the light transmittance can be varied across the opaque and transparent spectrum by alternating voltage or temperature applied to the glass. In the suspended particle type, a polyhalite particle cross-linked polymer component is in liquid suspension between two glass panels, and the transparent application depends on the alternating voltage (Ghosh et al., 2015). In liquid crystals, there are crystalline composite materials with dispersed polymers, and light transmission is like that of a suspended particle (Shen and Li, 2023). However, thermotropic glass's opaque and transparent states are temperature-dependent, and a polymer gel layer is placed between the two glass (Ji et al., 2016).

EC window applications stand out in terms of their performance compared to their peers and have an essential position in the market. First of all, its internal mechanism consists of five layers: glass, electrolyte, two transparent conductive oxides, and EC. Cations in the ion storage layer are transported through the conductive film at voltages lower than 5 V and then injected into the active layer via an external

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circuit. The type of cation is a factor that modulates the coloration differently. Applying a reverse potential voltage causes a bleaching reaction, and the glass becomes transparent again. Bleaching and coloring through redox reactions mainly occur in the EC window. The electrolyte is the layer that guarantees fast color change (Wu et al., 2023a). The switching voltage range must not affect the electrochemical stability at the end of the process, which requires transparent behavior according to visible light. While EC windows have a different color spectrum at intermediate voltage values, the coloration is mainly retained even if open circuit conditions occur (Mardare and Hassel, 2019). In the most straightforward meaning, the electric field created by the voltage applied to the outside of the internal mechanism changes the optical and thermal properties of the glass (Bai et al., 2023). This allows the user to control the reflection, transmission, absorption, and emission of light (Malekafzali Ardakan et al., 2017).

Other smart glass markets are photochromic and thermochromic windows, which can adjust their transmittance with light intensity and temperature changes and react to environmental stimuli. Electrochromic windows, which offer dynamic modulation over a wide spectral range and are more sensitive to user comfort, are gaining the most market interest (Zhao et al., 2023). The main advantages of photochromics and thermochromics are that they don't require equipment configuration and electricity supply. In contrast, electrochromics require the setup above, making the eventual installation cost expensive and laborious. Although photochromic applications are more common in transition lenses, their use in smart lenses is limited because the user cannot control them at the ensemble level, and optical switching is closely related to light intensity. In thermochromic windows, where the dynamic modulation range is more limited than in electrochromic technology, the maximum visible light transmittance can be increased to a specific level.

Besides electrochromic, photochromic, and thermochromic glass, insulated glass units are also available on the market. This technology consists of two glass panels filled with argon gas, sealed at the edges, and using the air gap as insulation. Chromogenic coatings are fitted on the inner surface of the outer glass panel to provide insulation from extreme environmental conditions, better thermal management, and extended lifetime. Finally, the internal structures of the four technology types can be summarized in Fig. 1 (Wang et al., 2016).

When equipping buildings with EC windows, it is necessary to determine practical operations based on user reactions (Jain et al., 2022). In particular, some users dislike the screen effect created by the translucent window and, therefore, want manual EC window control and are not interested in automatic control. However, developing EC windows with thermally improved performance and a dimmable lighting environment could change their attitude toward automatic control (Papathanasopoulos et al., 2017). One of the exciting aspects of automatic orientation is that it can be integrated into EC window control strategies (Atangulova et al., 2024). Accordingly, lighting energy use, direct daylight control, uncomfortable glare, and its impact on interior lighting must be considered (Li and Wu, 2024). Considering the glass angular selectivity and the active switching effect, EC window oriented with a dynamic control strategy on south-oriented windows can eliminate the uncomfortable impact of high glare (Ahmed et al., 2023). However, set points and measured variables must be considered for effective optical properties and energy performance (Hoon Lee et al., 2020), and it is argued that the EC window positioned on the west front instead of the south will improve performance (Detsi et al., 2024). Therefore, the design parameters (location, front orientation, window/wall ratio, etc.) for buildings with EC window integration significantly affect visual comfort and energy/thermal performance (Malekafzali Ardakan et al., 2017). East, south, or west fronts and high window/wall ratios are expected to provide the highest energy savings, especially in hot climates (Dussault and Gosselin, 2017). In addition to visual comfort and design parameters, criteria such as dynamic solar energy gains and thermal performance in the climate chamber buffer region created for overheating risks should also be considered (Ajaji and André, 2015). In particular, thermal loads are reduced by adjusting the EC window to the lowest transmission state (Villa et al., 2024). It is also emphasized that indoor heat testing can improve energy-saving performance (Es-sakali et al., 2024) and that the optimum temperatures for each sample can be obtained in an experimental test setup (Martín-Chivelet et al., 2018). Therefore, EC windows' optical and thermal features differ, and user-based control strategies must be carefully considered. Comfort-based strategy, in particular, may slightly increase the minimum primary energy required for energy optimization (Suzuki et al., 2022). It also saves more than 20 % of energy compared to the selective glazing legally required for commercial buildings. Also, combined with innovative chromogenic technologies, it can guarantee annual energy savings of up to 25 % in buildings (Cannavale et al., 2018).

1.1. Motivation and contribution

Studies on smart glass on many topics, such as user behavior, visual comfort, energy utilization, design parameters, optical and thermal properties, innovative technologies, and performance-indexed control methods, are ongoing and attract the attention of researchers. Table 1 carefully addresses the related studies' methods, objectives, and findings. Recently, efforts have been ongoing to address the current shortcomings of EC technology regarding robustness, optical modulation, charge transfer and long service life. Polymer-dispersed liquid-crystal devices (PDLCs), suspended-particle devices (SPDs), micro-blinds, and numerous other innovative technologies that work on EC window logic (voltage as stimulus and light transmission as response) are relatively mature and under continuous development (see Section 2.1). However,

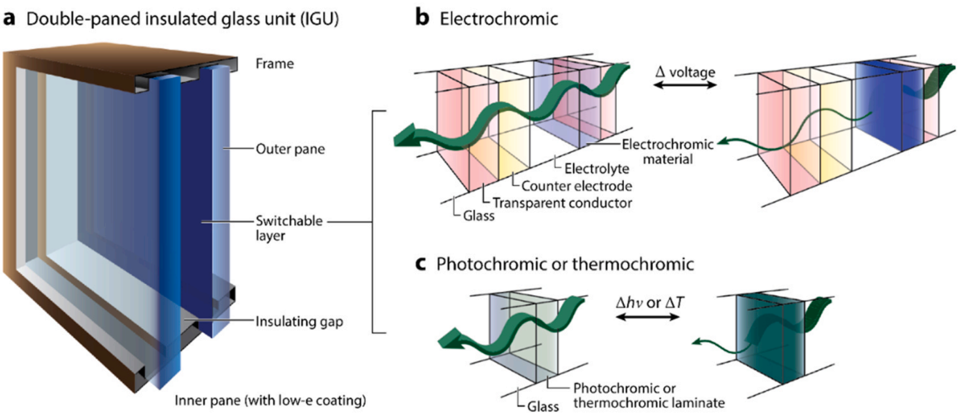


Fig. 1. **(a)** Double-panel insulated glass unit, **(b)** Electrochromic smart glass color, **(c)** Photochromic and thermochromic smart glass color (Wang et al., 2016).

Table 1
Comparison of related studies based on smart glass technologies.

Ref.	Method	Objective	Finding
(Park et al., 2019)	The Quick Energy Simulation Tool (eQUEST), a building energy interpretation program, was used.	Analyzing the beneficial effects and thermal and optical properties on the building's energy performance.	Lighting energy consumption was increased by 8.89 % by reducing visible light transmittance.
(Wu et al., 2023b)	Four strategies have been proposed and tested to enhance the design and performance using novel layered photovoltaic shading technology.	To realize optimized window design using PV shading technology and propose strategies for adjusting the indoor lighting.	The lighting strategy increased the useful daylight illumination (UDI) to 79.88 %, saving 13.7 % energy.
(Han et al., 2023)	Based on the glare calculation model, the effectiveness of the proposed design method for a south-oriented window in an office building is verified via a Grasshopper-based dynamic simulation tool.	Propose the optimal split panel configuration design method for the minimum colored area clock.	Intolerable glare was avoided by up to 95.3 %, and a UDI index of up to 73.3 % was achieved. Lighting energy consumption has been reduced by up to 29.8 %.
(Kim et al., 2021)	EnergyPlus analyzed energy consumption over time, and the Rhino Grasshopper's Ladybug Plugin was used to obtain data on the control groups' heating and cooling loads.	Analyzing the energy usage over time, determining its optimum properties, and comparing its energy saving, heating, and cooling performance with existing architectures.	A 46.2 % heating and cooling energy load improvement was obtained for the west-oriented smart technology.
(Cardoso et al., 2019)	A new design concept controls visible and infrared solar radiation simultaneously.	Defining a new design concept that can be easily implemented at the industrial level.	Heating and cooling loads are reduced in regions with a wide temperature range.
(Fathi and Kavoosi, 2021)	In DesignBuilder, a high-rise office building is modeled in three dimensions. Weather data is entered into the model, and EnergyPlus realizes the impact of energy consumption annually.	Investigation of the effect on energy consumption in high-rise office buildings such as building integrated photovoltaic and building energy management systems under different climatic conditions.	Combined with other equipment, it reduces energy consumption by up to 35.6 %.
(Zhang et al., 2023)	A modular illuminance level test bench was established, and an optical simulation model was developed for the Daysim program. EnergyPlus analyzed energy-saving potential.	Modular design with PV on the lower layer, smart glass on the middle layer, and transparent area on the upper layer to improve lighting comfort and energy-saving performance.	The design improved UDI by up to 75.3 %. Compared to conventional windows, up to 15.8 % energy savings were achieved.
(Li et al., 2023a)	A full-scale climate chamber test bed was created in a tropical climate.	Investigation of the thermal and visual performance of a full-scale test bench.	Approximately 80 % of the interior heat flow is efficiently reduced, improving thermal performance. Using a bleached technology means 39 % of daylight hours are glare-free, and lighting comfort is improved.
(Khatibi et al., 2022)	The control algorithm is driven by the user's status in the building. The developed deep learning model predicts the decision variables if the user is not in the building. DesignBuilder and EnergyPlus performed simulations of the hybrid algorithm in different climatic conditions.	Evaluating the effects of a new hybrid control algorithm that manages the transparency status based on the existence of users in the building on the energy and light comfort.	The hybrid control algorithm increased energy savings by up to 26.1 % and improved energy efficiency by 8.44 % compared to its constituent algorithms.
(Li et al., 2023b)	Two large-scale air conditioning rooms were created, one with double smart glass and the other with single glass that can be tinted in gray.	Experimental analysis of the effect of energy saving and improved thermal performance of indoor areas in tropical climatic conditions.	Thermal comfort increases by 50 % compared to single glass, and a choice of colors guarantees energy savings of up to 19 %.
(Wu et al., 2019)	Decentralized daylight control to realize tint control with less installation and commissioning and to avoid uncomfortable glare in buildings. Real-time lighting simulation is achieved by monitoring glare distribution in the sky and planning tint control—empirical validation against conventional control methods.	Planning of compact automation management using embedded photometric devices to control the tinting status of the divided technology depending on monitoring the sky glare distribution and real-time illumination calculation of the interior area.	Work plane illuminance and daylight glare probability variation are kept below 62 % and 85 %, even under conditions of rapid daylight change.
(Budaiwi and Abdul Fasi, 2023)	A dynamic simulation was performed using the advanced building simulation tool DesignBuilder, and the two control drivers for the smart technology were compared in terms of daylight level and glare control of the strategy.	Evaluate energy saving and visual comfort potential for office buildings in hot-humid climates.	Thanks to the strategy, which utilizes daylight control but limits visual comfort, energy savings are increased by 23 % while visual comfort is not compromised.

the choice of technology in the smart glass market depends on user behavior, as optical, electrical, and thermal shortcomings remain. Smart glass, envisioned to replace standard glazing in future buildings, can meet minimum lighting requirements with lower energy consumption indoors by adequately managing its compatibility with artificial light sources and sunlight. Indoor lighting control strategies that keep pace with innovative smart glass technology developments are more valuable than ever in transitioning to a sustainable city and society.

A general gap in the literature is the comparative analysis of smart glass' contribution to energy savings, considering their advantages over their peers, such as widespread use and ease of control (Cannavale et al., 2020). The market share of smart glass is growing, particularly with the increased adoption of technologies such as polymer-dispersed liquid-crystal (PDLC) glass, alongside other types like photochromic, thermochromic, and insulated glass units. Optimizing the management of smart glass in response to varying sunlight conditions and enhancing energy efficiency and lighting quality in the presence of artificial light sources remains an area of active research and holds significant potential for future advancements.

This study is original in investigating PDLC-based smart window technology by focusing on a less-explored, specific location rather than the extreme climates typically studied in PDLC-based energy research. It presents a novel approach by developing a comprehensive topology that meets minimum lighting requirements by integrating artificial light source management, weather conditions, and user behavior into PDLC-based smart glass technology. This research offers novel insights into PDLC-based smart window performance by designing a test cell that simulates an office environment with a PDLC-based smart window, a glass with 80 % light transmittance (IG80), and a dimmable LED lamp and by analyzing five distinct scenarios with varying control algorithms. The study aims to identify optimal control strategies for balancing lighting quality and energy savings, thereby contributing new knowledge to energy-efficient building technologies and addressing gaps in understanding PDLC-based smart windows under specific, under-researched conditions.

This paper is organized as follows: Section 1 presents the Introduction, including the literature review and originality, while Section 2, Methodology, discusses the test bench, materials, system design, flow diagram, and scenarios. Section 3 evaluates the performance analysis results, such as comparative assessment, cost-benefit relationship, and feasibility of the planned method. Conclusions and study gaps are discussed in Section 4 under the heading Discussion, while conclusions and suggestions are presented in Section 5.

2. Material and methodology

2.1. Recent advances in smart glass

This section reviews recent research efforts to address the current shortcomings of smart glass technology. To exemplify the technological progress towards smart glass, EC, PDLCs, SPDs, and micro-blinds are also discussed, which are partially mature compared to other innovations. While advances in smart glass technology are not limited to these, the analysis of the rationale behind focusing on these smart glasses is further elaborated.

- **EC technology**

Tungsten oxide (WO_3) is one of the most favorable electrochromic properties that can guarantee high optical modulation and coloration efficiency. ECs based on WO_3, which can permanently and reversibly change their optical properties in reaction to an electrical stimulus, must be characterized regarding their durability ability for operation-specific challenges. Here, durability refers to the ability to sustain charge transport between the EC film and the electrolyte or between two EC films. Sustainability is measured according to optical modulation, charge transfer, resistance to degradation by solar radiation over long periods, chemical ruggedness concerning interfaces, and adequate shelf life (Granqvist et al., 2018). To guarantee the long service life of EC devices and high optical transmittance modulation, durability capabilities are critical in smart glass technology. Thus, it is essential to consider annealing for an entire device to achieve high operational efficiency. In particular, using indium tin oxide (ITO)–based films with high transparency and low electrical resistivity in EC technologies, achieved by sputtering high substrate temperature, requires an evaluation of the consequences of high temperature on EC layers. The effects of annealing on the film durability of substrates for appropriate temperature ranges should be investigated (Atak et al., 2021a). Therefore, annealing at 300°C and above will deteriorate electrochromic properties and decrease optical transmittance variation. Inappropriate temperature ranges and annealing can affect transmission and optical performance. Variables such as charge density and coloring efficiency depend on the number of anneal' temperatures and electrochemical cycles. On the other hand, the effects of the oxygen-argon gas flow rate existing during the sputter-deposition process on electrochromic tungsten film durability should be analyzed (Atak et al., 2021b). After a series of electrochemical and other electrical measurements such as cyclic voltammetry, working and counter&reference electrode, it was observed that the charge capacity dropped and the high potential value for the onset of electrochromism decreased. Overall, their limited durability under electrochemical cycling and blue coloration in transmission are two significant barriers to WO_3. However, adding titanium and molybdenum can significantly eliminate these problems (Arvizu et al., 2017). However, high nickel concentrations shouldn't be applied to minimize compromising EC performance (Morales-Luna et al., 2016).

Another approach that could change the approach to EC technology is rejuvenating the original properties of degraded EC films (Wen et al., 2015). Adding Li^+ to oxygen-deficient films significantly leads to a substantial increase in optical absorption (Triana et al., 2015). Moreover, their optical modulation and reversibility ability are reduced due to ion trapping, which is believed to be irreversible at long periods of $Li+$-ion exchanges in cases of amorphous WO_3 films used as cathodes in EC devices. A remote extraction strategy operated at a constant current overcame the problems and rejuvenated the WO_3 films. Also, galvanostatic trapping can regain electrochromic performance (Wen et al., 2016c). While it is an adaptive approach for other ionic-based devices, the rejuvenation process can also be applied to galvanostatic, potentiostatic (Wen et al., 2016a), TiO_2 (Wen et al., 2016b), and MoO_2 (Arvizu et al., 2016) instead of WO_3.

- **Polymer-dispersed liquid-crystal (PDLC) technology**

PDLCs originate from the dissolution of liquid crystals in liquid polymer followed by dispersion and solidification or curing of the polymer (Wikipedia, n.d.). It is placed between two layers of glass or plastic, including a thin layer of transparency. The curing conditions determine the droplet sizes and, thus, the smart glass operating characteristics. The droplets are randomly arranged when voltage is supplied to the transparent electrodes. The resulting electric field aligns the liquid crystals, allowing less light to scatter in the droplets. Most of the light is dispersed into the environment, resulting in a transparent look at the end of the process. However, the higher the voltage, the less light is scattered by the misaligned liquid crystals. It is possible to control light and heat by using color tints and particular inner layers. It has many applications, especially in smart glass and screen applications. However, this technology's maturity and practical performance depend on several factors. Thanks to its economic viability, it is characterized by various commercial uses, such as automotive, building, and consumer electronics.

Technological innovation is ongoing to improve the light transmission, response time, energy efficiency, and endurance of PDLCs. It is a relatively mature technology in continuous development. One of its main drawbacks is due to its electrical-optical properties. Low contrast ratios and poor visible light transmission can exemplify this. Although PDLCs with high contrast and low voltage supply are desirable, the balance between contrast and supply voltage needs to be carefully evaluated (Meng et al., 2021). Another concerning aspect is that in the closed state, the degree of arrangement of molecules adjacent to the polymer network in the liquid crystal (LC) results in high transmittance and low contrast (Li et al., 2020). Besides tuning the electrical-optical properties, work is also underway on developing functional PDLCs. Although traditional and innovative designs exist, electrical energy consumption is another barrier. In this context, bistable PDLCs stand out with their lower energy consumption. However, this technology encounters design and manufacturing limitations due to the variety of LCs stabilized in the polymer. It requires a complex and costly manufacturing process to achieve high performance and durability based on user needs and implementation requirements. While challenges remain, with the necessary innovations, PDLC technology can address temperature control. Moreover, near-infrared light transmission can be obtained using dual-band modulation in addition to visible light by adding infrared light-absorbing nanomaterials to PDLCs (Li et al., 2017). Investigating different electrode materials can decrease ITO layers' high cost and low resistance with low-performance characteristics (Hosseinzadeh Khaligh et al., 2015). Ideas to replace ITO in the research focus include solution-processed SnO2 film on Au mesh electrodes, nylon six nanofiber-reinforced cellulose acetate (NF-r-CA) films, silver nanowires, and NF45-r-CA electrodes. In addition, the TiO_2/Ag (Cu)/TiO_2 type electrode design by (Huang et al., 2019) could simultaneously realize high transmission and heat shielding. Focusing on designing PDLC smart glass with low driving voltage for safe and energy-efficient operation in PDLCs with trends and challenges is laborious. To this end, it is necessary to maintain the size of the polymer networks and to do so, use low surface energy polymers. Regardless of how the LC molecules are placed in the droplets, avoiding light scattering at the interfaces between polymers and LCs is essential. The angle dependence of PDLC transparency in a sufficient electric field is a known phenomenon, and the light transmittance needs to be appropriately adjusted based on the angle of observation to avoid a blurred view. For details on the current market, challenges, and future directions, please look at the study by Zhang et al. (2022).

- **Suspended-particle device (SPD) technology**

In this technology, a thin film laminate consisting of nanoscale particles resembling a rod is suspended in a liquid and placed between two pieces of glass or plastic. When no voltage is applied, the suspended particles are randomly arranged and block the transmittance of the light due to absorption. When voltage is applied, the particles align, allowing light to pass through. The tone of the glass and the amount of light transmitted depend on the orientation of the suspended particles relative to the voltage level (Wikipedia, n.d.). Switchable devices, remote controls, or automated systems can be used to reduce the effects of glare and heat gain in obtaining the relevant electric field that adjusts transparency (Ghosh et al., 2016a). On the other hand, its technological maturity varies depending on its commercial use, performance, and limitations. It is widely used in automotive, building glazing, sunshade systems, and oversized glass panels. It offers a wide optical transmission range with fast and controllable light transmission. SPD films are primarily preferred in plastic-type. The reason for this is to eliminate the bulging effect and leakage issue. In addition, dihydro cinchonidine bisulfite or herapathite chemicals are more commonly used for small particles suspended in the film. However, hydrogels based on conventional polymers with micrometric reduced graphite oxide particles trapped in the active layer can make SPDs more accessible and cost-effective (Soares et al., 2023). In this way, the swelling of the hydrogel can be reduced by up to 28.3 %. In addition, depending on the voltage applied to the SPD glass, the response in light transmission can be accelerated by up to 38.6 %. A different benefit is specific to the Warburg impedance. Using the relative impedance due to ion diffusion can measure optical properties, switching speeds, chemical stability, and durability (Gadgil et al., 2024). Improving porous polymer layers can serve for an enhanced performance. SPD glass doesn't cause a power drop even at high temperatures (Ghosh and Norton, 2017). It provides fast color change and dynamic tuning of colors for the user's benefit, regardless of window size. Therefore, a tinted view from transparency to chromaticity can be obtained in less than a second. It can effectively decrease energy costs and provide almost instantaneous lighting control. It does not cause fading if the furniture is used in the environment and guarantees a significant reduction of ultraviolet radiation (Nundy and Ghosh, 2020). Window decorations are a sustainable solution while eliminating the need for curtains and sunshades. Thanks to the solar heat gain coefficients (SHGC), they are adaptable to heating and cooling loads and increase energy efficiency (Nundy et al., 2021).

Relatively mature and constantly advancing SPDs have specific limitations—for example, chromatic aberration or undesirable variations in light transmission under specific operating conditions. Although significant energy savings are potential, costly manufacturing processes and high voltage requirements must be overcome (Ghosh et al., 2024). Long-term durability is not yet a known phenomenon. Increased U-value and controllable visible light transmittance improve its use in warm conditions. UDI improves visual comfort indoors in terms of correlated color temperature (CCT) and color rendering index (CRI) (Ghosh et al., 2016b). Despite its high performance for warm climates, it should be emphasized more indoors' sunlight transmittance and SHGC in cold temperatures. Hence the recent focus on installing low-coated or vacuum glass. A better performance can be obtained in an opaque state by not causing power consumption at high energy tariffs or outages during the daytime. The impact of glazing with SPDs on heating and cooling loads has been measured in Anseong, Korea (Ko et al., 2020). This study considered the SHGC range, but control strategies needed to be more effectively implemented; SPD reduced 29.1 % and 15.8 % of electricity consumption for cooling and heating. The annual electricity consumption of the office building could be lowered by 4.1 %. SPDs encourage their use in automobiles, observation decks, trains, and museums; but the disadvantages that limit their widespread use should also be considered. The amount of suspended particles limits the optical contrast, while actions to decrease visual defects lead to reduced switching speed and stability issues (Lemarchand et al., 2014). The dynamic environmental impact in outdoor environments poses a challenge for SPD operations, and when it comes to weather conditions, especially haze must be eliminated (Costa et al., 2019). Advanced material design and manufacturing processes should be pursued to optimize particle dispersion and improve optical modulation capabilities. Innovative R&D efforts are currently ongoing to achieve optimistic service in terms of performance, durability, and cost-effectiveness.

- **Micro-blind technology**

Micro-blind technology is another innovative smart glass technology nearing maturity and can potentially control light transmission. The metal layer, named after the tiny thin metal blinds that roll over the glass, is created by magnetron sputtering and laser or lithography. The micro shutters, which are inorganically biased curled electrodes with a size of 100 μm (Michael et al., 2023), are a key component of this technology. A transparent conductive oxide layer (TCO) glass substrate is used, while an insulator is deposited between the rolled metal layer and the TCO to eliminate electrical disconnection activity. The technology uses microscale shutters built into the glass panels, and the light transmission is adjusted by mechanically opening and closing the shutters. As the blinds are rolled based on the voltage value, the potential difference between the rolling metal layer and the TCO stretches the micro-blinds via the electric field, thereby preventing light transmission. This technology is attractive due to its switching speed, UV resistance, customized appearance, and transmission (Wikipedia, n.d.). It also does not require expensive indium-tin-oxide conductive layers and enables active and deactivate switching in milliseconds (Brzezicki, 2021). Each micro-shutter can be controlled independently, providing flexibility in daylight control. It can help reduce energy consumption by regulating indoor temperatures. In this respect, it has found its place in oversized facades, commercial buildings, offices, and industrial applications. However, as it is not yet fully mature, the issue of micro-blinds loosening when triggered by a weak electrostatic stimulus needs to be carefully considered (Lamontagne et al., 2019). Long service life and durability require using high-quality materials in the manufacturing process. It has costly manufacturing limitations compared to other smart glass technologies to achieve reliable performance. Indoor micro-shutters accumulate dust and dirt, increasing operational maintenance costs and efforts. Clean working conditions are needed for visual attractiveness and system efficiency.

- **Other immature technologies**

Other technologies include transparent insulation material fillings, air sandwich, solar absorbing, dynamic emergent, electrically tunable, nanocrystal in-glass composites, elastomer-deformation tunable, liquid infill tunable, electrokinetic pixel, transparent PV/solar cell and opto-fluidic glass, heat insulation solar glass and localized plasmon resonance technologies. The study by Michael et al. (2023) can be reviewed for details of each innovative technology class.

2.2. Adaptability of the Proposed Control Strategy

As mentioned, every technological advance in the smart glass market has pros and cons, and ongoing efforts are being made to address the current shortcomings of each smart glass, including PDLC. The market of innovative technologies has yet to be made clear; however, the PDLC-based smart window, which is partially mature compared to its peers, has often been favored in research. On the other hand, each innovative technology considers voltage as a stimulus and adjusts the light transmission with different internal working mechanisms. These technologies, which will be incorporated into future buildings' glazing, need to collaborate with artificial light sources for indoor lighting. The lighting control strategy proposed in this study can manage artificial light sources and innovative smart glazing technologies to provide the desired indoor lighting comfort. Identifying a feasible indoor-specific control method based on their trade-offs will take technological efforts' electrical and optical performance to the next step. Although the technology of smart glass and, thus, their actions to adjust the light transmission in their internal mechanisms may vary, the proposed control strategy can be considered an adaptive approach since it is not affected by technological progress and lighting efficiency is adjusted according to the voltage. The smart glass technologies' specifications are compared on the market in (Hafnaoui et al., 2024). The three glazes compared in the market, which are relatively prominent in smart glass technology, have similar characteristics, especially in terms of lighting performance. Tests on relatively mature and still developing smart glass technology could prove the practicality of interior-specific control strategies for the lighting and electrical sectors. In this context, integrating lighting control with innovative smart glass technology can accelerate the transition to sustainable cities and societies and enhance the position of governments in climate action by achieving the desired performance indoors and outdoors.

Table 2
Technical details of dominant active smart glass technologies on the market.

Specifications	EC	SPD	PDLC
Technology	Electrochromic	Suspended-particle material	Polymer-dispersed liquid crystal
T-Op / Tr	On-OFF	On-OFF	On-OFF
T_{vis}	60–1	65–0.5	75–50
R_{vis}	5–10	6–12	6–15
SHGC	0.46–0.06	0.57–0.06	0.69–0.55
UV Trans (T-Op / Tr)	0.4–0	0.1 – 0.1	0.5 – 0.5
Operating temperature	20 °C - 70 °C	−40 °C - 120 °C	20 °C - 70 °C
Power voltage	DC	AC	AC
Power requirement for state transition	2.5 W/m^2	5 W/m^2	5 W/m^2
Switching speed	5–12 min	1–3 s	40 ms
Cost	Medium	Highest	High
Durability	50 year	20 year	10 year

EC: Electrochromic; **SPD:** Suspended-particle devices; **PDLC:** Polymer-dispersed liquid-crystal; T-Op / Tr: Transparent-opaque/translucent; **T_{vis}:** Visible transmittance; **R_{vis}:** Visible reflectance (%);**SHGC:** Solar heat gain coefficient; UV Trans (T-Op / Tr): UV transmission (transpatent-opaque/ translucent) (%)

2.3. System design (block and flow diagram, decision tree structure)

- **Test bench**
  The room's temperature and light intensity data in the experimental test bench are monitored in the sensor box via NTC and LDR, respectively, and transferred to the Arduino MEGA 2560 microcontroller. While the control strategies are developed in Python, a similar platform is used for remote communication and control of the microcontroller. At the end of each cycle, the calculated lighting parameters are saved on the SD card module, while a step motor controls the light transmission of the PDLC-based smart window. An AC voltage chopper is also used to obtain the desired driving voltage. After creating the PDLC-based smart window driver, the microcontroller supplies the output voltage power circuit to get the suitable input voltage level for the LED driver. The final block diagram for the scenario-based test procedure is shown in Fig. 2.
- **Test procedure of the test bench**

The test procedure is started by selecting one of the five scenarios developed in Python. The start and end times of the test are determined by considering the sunrise and sunset times, and the test bench is run at this time interval. After sunrise, 10-bit values (0–1023) are taken from the five LDRs in the sensor box. The collected data and the lux meter values are compared with the previous ones. Based on the data analysis, a polynomial regression method is performed, and the formulations derived are used to determine the lux values with an error of less than 10 %. Illumination calculations must be made using data from several procedures, including polynomial regression. Knowing how to calculate measured data is a valuable approach. Here illumination is determined from the ratio of the luminous flux emitted from a light source at a given solid angle to the area within the visual limits of the eye. The angle between the direction of the luminous flux from the light source at a given solid angle and the normal of the surface to be illuminated is denoted by α. The distance between the light source and the illuminated surface is d. A is the area of the surface to be illuminated. The cone- or pyramid-shaped part of space through which a given luminous flux passes is denoted by the solid angle, Ω. The 4 π steradian is usually considered due to the prevalence of the spherical volume use case, and E and U denote the illuminance level and uniformity factor. Φ states the luminous flux, and the luminous intensity by I. $V(\lambda)$ is the photopic spectral sensitivity corresponding to each wavelength. At the same time, Φ_e is the amount of radiant energy emitted per unit time, including radiometric directions beyond visual limits. The spectral sensitivity of the eye is often considered. While λ is the wavelength, the coefficient K_m is the luminous flux corresponding to the 1/683 W radiation power of a monochromatic light source at 555 nm (in the relevant wavelength, the eye is most sensitive in standard weather and daytime vision). When the radiation power is 1 W, it is considered 683 lumens. Accordingly, the illuminance and uniformity factor from two different perspectives are calculated by Eqs. (1) and (2) (Ni et al., 2022; Zhao et al., 2018).

$$E = \frac{K_m \int_{380}^{780} \Phi_e(\lambda).V(\lambda).d\lambda}{\Omega.A} = \frac{I}{d^2}\cos(\alpha) \tag{1}$$

$$U = \frac{E_{\min}}{E_{\max}} = 1 - \frac{I_{\max} - I_{\min}}{I_{\max} + I_{\min}} \tag{2}$$

After the polynomial regression, according to the available scenario, the control algorithm is processed, and the sensor and calculated values and the dimmer percentages of the PDLC-based smart window and LED lamp are saved on the SD card at the end of each cycle. This process is continued until the end of the day, and a serial communication protocol is used with Python developed to provide remote access to the data stored on the SD card at the end of the day. The flowchart of the test procedure is shown in Fig. 3, while the data collected throughout the day

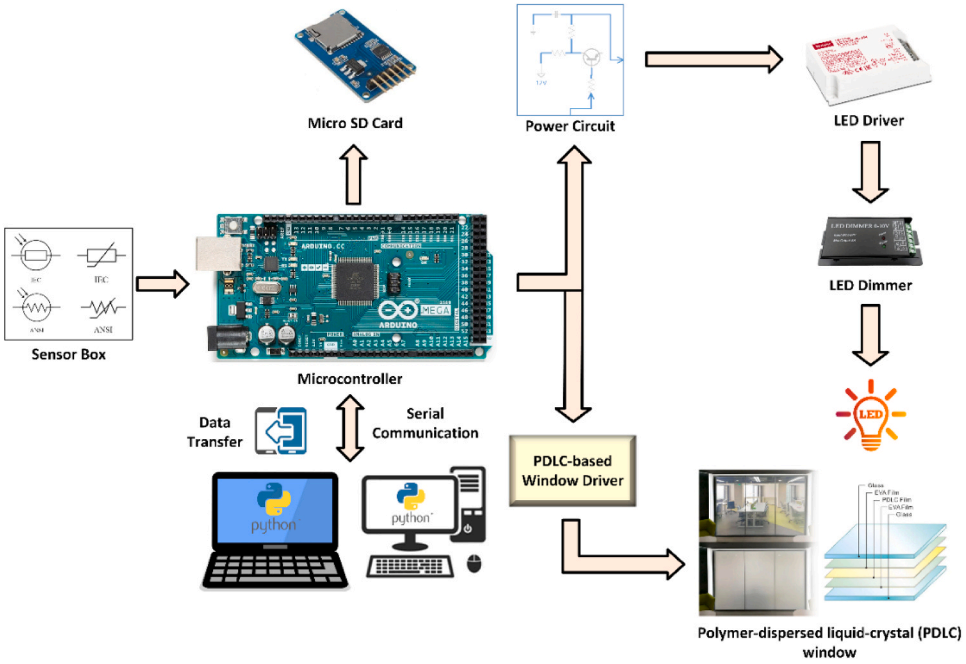


Fig. 2. Test bench.

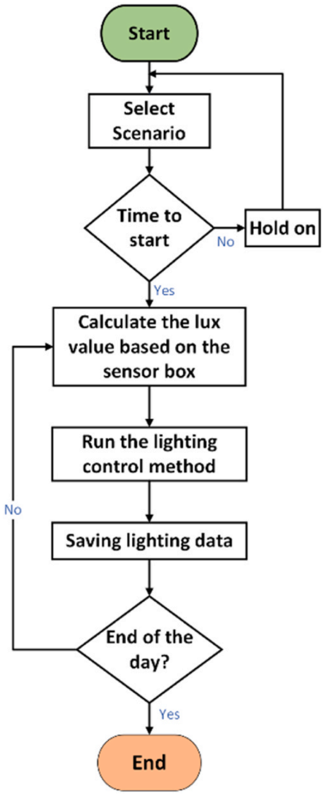


Fig. 3. Overview of the main test bench process.

is saved in an Excel file.

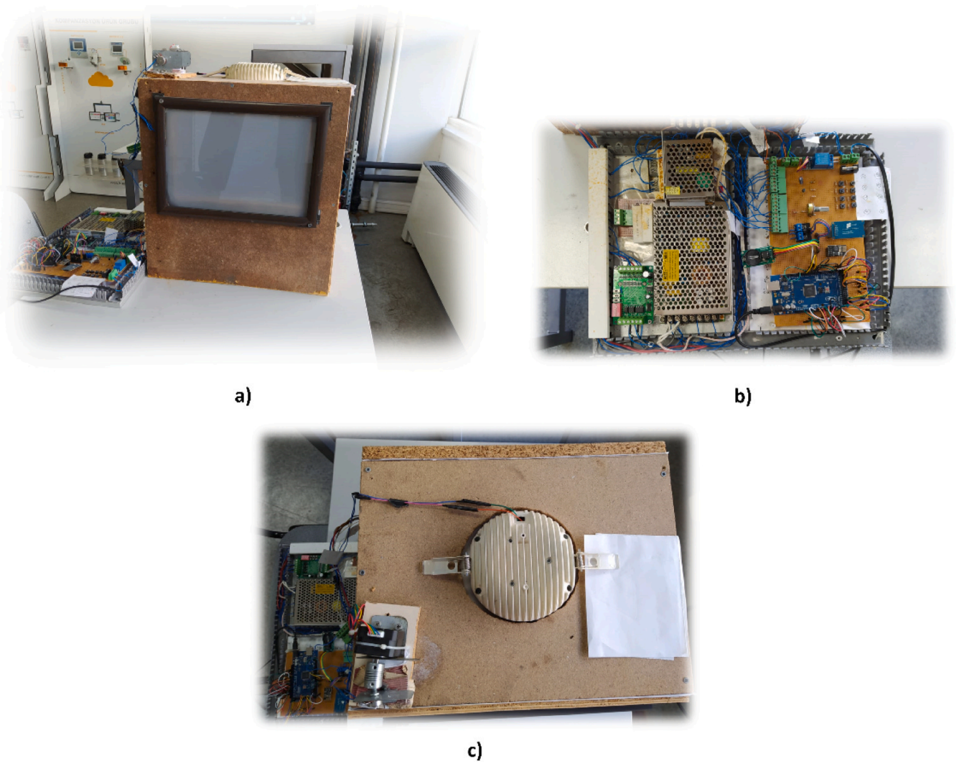
- **Technical details of the test bench**

The experimental cell comprises sensors, a polymer-dispersed liquid-crystal glass, and an LED lamp. It is a rectangular prism on an MDF base with dimensions of 45 cm * 40 cm * 30 cm. The front side has a 20 cm * 30 cm window opening. Depending on the scenario being tested, IG80 and the PDLC-based smart window are fitted in the relevant window opening, and the tests are performed. Fig. 4 shows an overview of the test cell and test bench.

The location of the test cell is an essential issue for a successful test procedure, considering the direct influence of solar radiation and weather conditions—changes in location or different weather conditions at the exact location cause significant differences in test results. The Yıldız Technical University, Department of Electrical Engineering research laboratory was chosen to conduct the experiments under similar weather conditions and in the same room. The average altitude of the laboratory is 90 m, with 2373 days of sunshine per year. In addition, the number of heating and cooling degree days are 1865 and 3433.7.

The glass types to be tested for experimental accuracy have similar dimensions, apart from the influence of weather and ambient conditions. The IG80 glass, widely used in the market, was used for comparison. The comparison was made to question the advantages and disadvantages of the PDLC-based smart window and their use with LED lamps. The window sizes and specifications of IG80 and the PDLC-based smart window are explained in Table 3. Besides the mechanical properties, the optical attributes of the PDLC-based smart window must also be known to determine the effects of the proposed control strategy on lighting efficiency. Visible light transmission is more than 75 % and 55 % for the on and off state. Parallel light transmission promises higher rates than 68 % and 1 % for the on and off state. The fog degree in both cases is < 7 % and > 95 %, respectively. When the visual angle is 150 degrees, the UV blocking is proposed to be >97 % for the PDLC-based smart window used in the study. When the operating voltage is 60 V AC, the switching time is < 200 ms and > 10 ms for off-on and on-off cases. The power consumption is 8 W/m^2, and the operating temperature range is 0°C-50°C. The service life promised is over ten years.

In addition to the size and position properties, an integrated driver model based on a non-switching AC chopper was developed to adjust the PDLC-based smart window light transmittance. A simple voltage divider circuit is created with the help of a potentiometer. At the same time, a NEMA17 stepper motor driven by a TB6560 is used to automatically control the PDLC-based smart window driver with low power consumption. The stepper motor is mounted on the potentiometer shaft via



a)

b)

c)

Fig. 4. View of the test bench with PDLC-based smart window at different viewing perspectives: **a)** front view, **b)** power electronic circuits, **c)** top view.

Table 3
Window size and specifications.

Window type	Window-to-wall ratio	External wall area (m^2)	Window width (m)	Window height (m)	Light transmittance (%)
IG80	0.33	0.18	0.3	0.2	80
PDLC-based smart window	0.33	0.18	0.3	0.2	2–60

coupling.

When there is no light source other than daylight and an artificial lighting source in the experimental cell, the illuminance level should be set to 500 lx for office conditions. A 10 W Siobi Dimmer LED (Sunlight) was used as the artificial lighting source and mounted on the cell ceiling. LC1x30-E-AN is the driver used to ensure the proper operation of the LED. Since the input voltage in the 1–10 V range required for the LED driver is unavailable from the Arduino Mega2560, a simple power circuit boosts the microcontroller's voltage output in the 0–5 V range.

2.4. Scenarios and control strategies

The optimal lighting method for the office model was analyzed for five different scenarios. As specified in the EN12464 standard, the average illuminance and uniformity factor for the office area must be 500 lx and 0.8, and these relevant values represent the reference level for the analysis of the results. The lighting method and the scenario vary depending on the type of glass, the existence of LED lamps, and the possibility of dimmer percentages, as explained in Table 4. Also, the lighting control algorithm doesn't consider heating and cooling loads, ambient temperature conditions, and potential energy consumption. Changing weather conditions and climate are also included in the process thanks to smart glazing that can adjust daylight transmission. Issues such as durability and service life are evaluated with the test environment's humidity, temperature, and pollution. The analysis and evaluation of the results focus on the illuminance level, uniformity factor, dimmer percentages, and energy consumed in the artificial light source (indirectly, energy savings).

Table 4
Scenarios of the study.

Scenario	Sub-scenario	Window type	LED	LED dimmer	PDLC dimmer
1	A	IG80*	Off		
	B		On		
	C		On	✔	
2	D	PDLC-based	On		✔
	E	smart window	On	✔	✔

IG80: Glass with 80 % light transmittance; **PDLC:** Polymer-dispersed liquid-crystal

Sub-scenario A includes the LED lamp in the closed state and the IG80 glass fitted in the relevant window opening. In this sub-scenario, the daylight-induced illuminance level in the test cell is determined by the sun's movement without an additional artificial light source. Sub-scenario B is represented if an LED artificial light source is available in addition to daylight. In this sub-scenario, since the effects of daylight are determined, the energy consumption of the LED is considered, and its contribution to the illuminance level and the uniformity factor, and therefore to visual comfort, is discussed. The dimmer control of the LED lamp with the developed algorithm is performed in Sub-Scenario C, and the effects on energy consumption without compromising visual comfort by dimming the LED lamp depending on the daylight conditions and turning it off in specific periods are questioned. In addition, the control method was developed to ensure the desired average illuminance level is operated. In the lighting control method, if the uniformity factor and illuminance level are below the reference, the LED dimmer level is increased, and conversely, the LED lamp is dimmed. If the reference level is acceptable, the dimmer level is not changed. If the coexistence of the LED lamp with daylight without a dimmer is considered, then Sub-scenario D for the PDLC-based smart window is considered. A constant artificial light source is considered to match the illuminance level in the test cell to the standard. The PDLC-based smart window transmittance blocks solar radiation that could cause glare. The transmittance control also guarantees light comfort for the office model. Although the LED lamp dimmer is unavailable, the lighting control method has been developed as in Sub-scenario C and serves the PDLC-based smart window. If the ambient light level is above the reference level, the dimmer and, therefore, the light transmittance of the PDLC-based smart window is reduced, and vice versa.

A different control algorithm is operated in Sub-scenario E, which considers adjusting the PDLC-based smart window light transmittance and the LED lamp dimmer. There are two alternatives for lighting comfort, and the dimmer control of the LED lamp also saves energy. The control algorithm is developed by integrating the LED lamp dimmer control in sub-scenario C with the PDLC-based smart window control in sub-scenario D. If LED dimming is insufficient, the PDLC-based smart window control is switched to. However, dimming or reducing the PDLC-based smart window dimmer is unnecessary when the ambient illuminance level is higher than the reference level. It is required that the LED lamp is entirely off or about to turn off before reducing the PDLC-based smart window dimmer to utilize the energy from sunlight as much as possible and reduce energy wastage. Accordingly, if the ambient illuminance level is above the reference level, the LED lamp is switched off first. If the desired reference level is still not reached, the light transmittance of the PDLC-based smart window is reduced by reducing the dimmer. The room’s uniformity factor reduces as the PDLC-based smart window light transmittance decreases. Therefore, the uniformity factor must be greater than the reference level for dimming the PDLC-based smart window. The control algorithms developed specifically for sub-scenarios C, D, and E is shown in Fig. 5 and Fig. 6.

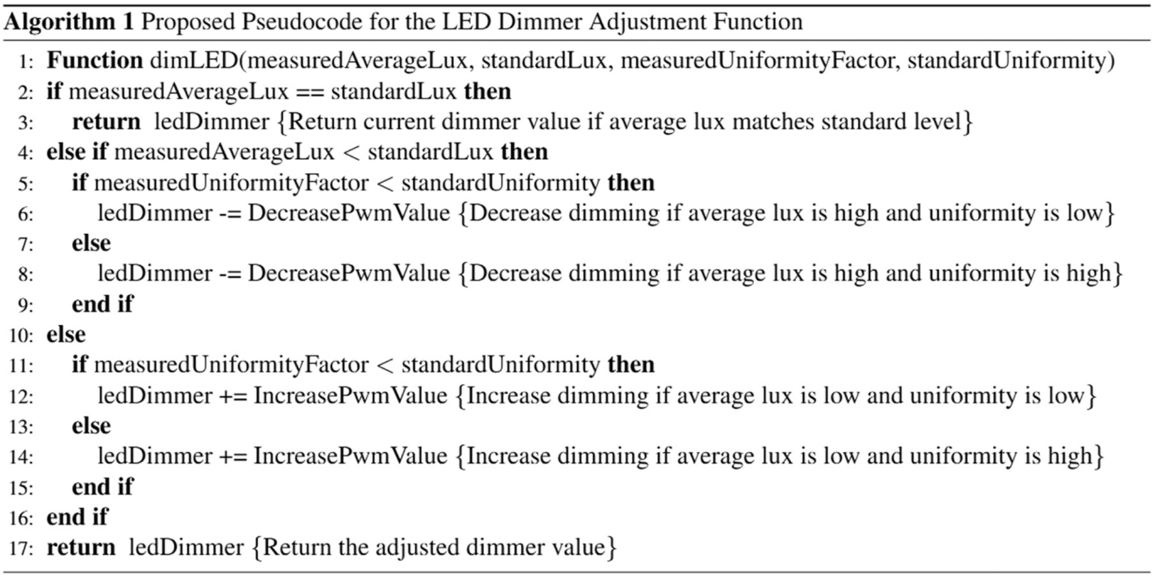
3. Results

This section compares lighting comfort (average illuminance level and uniformity factor), energy savings (daily energy consumption), and dimmer percentages for energy and illuminance level for five different scenarios. The plan was realized by obtaining the illuminance level, uniformity factor, energy consumption, and dimmer percentage data after scenario-based experimental tests for the office model. The scenario-based illuminance level curves obtained from the test bench and subsequently evaluated are shown in Fig. 7.

In sub-scenario A, no artificial light source (without LED lamp) and a fixed and uncontrolled IG80 glass with 80 % light transmittance were used. The objective is to determine the illuminance level provided by sunlight alone and the contribution of the uniformity factor. So, then, the illuminance level is well below the desired reference level. In sub-scenario B, the illuminance level is relatively high and well above the reference level, as the LED lamp is without a dimmer. For sub-scenarios A and B, the difference in illuminance level during the day exceeds 500 lux. In sub-scenario D, the LED lamp was operated without a dimmer, but the light transmittance of the PDLC-based smart window could be controlled. The illuminance values are, therefore, lower than in Sub-Scenario B in the middle of the day. Although the illuminance level is above the reference, the peak levels decrease in Sub-scenario B, especially during the day. In Sub-scenario C, despite the IG80 glass with uncontrolled light transmission, the LED lamp dimmer can be controlled, resulting in the second most beneficial lighting method in the daily illuminance curve. The superiority of the LED lamp dimmer control is noticeable, even though it does not have an adequate illuminance performance as in sub-scenario E. However, the weather condition during the test is the main criterion for the illuminance level. In areas or days with high solar radiation, sub-scenario C with the dimmer LED lamp will not be able to reduce the radiation, compromising the lighting comfort. On the contrary, the minor illuminance difference for sub-scenarios C and E will be reduced in regions with low solar radiation, resulting in unnecessary expenditure for the PDLC-based smart window and driver. Finally, inadequate illuminance in sub-scenario A and over-illuminance in sub-scenario B and D should be considered. Sub-scenarios C and E provide an acceptable lighting comfort level.

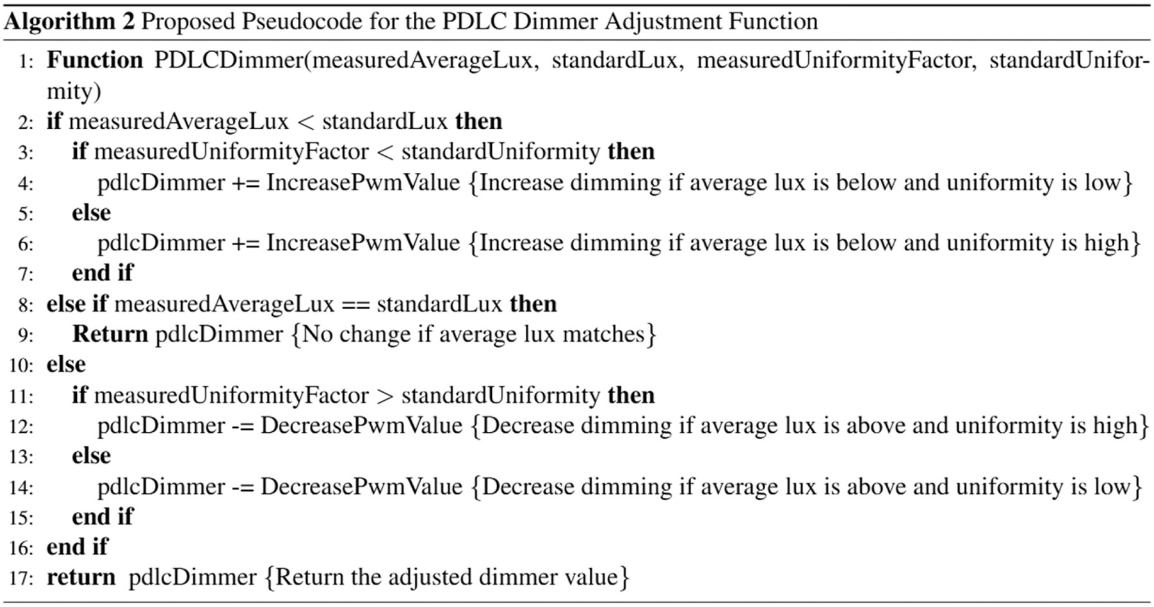
Another service in ensuring lighting comfort is to keep the uniformity factor at the desired level. The daily uniformity factor curves obtained as a result of the tests are shown in Fig. 8. The uniformity factor in sub-scenario A, where only daylight is available, is well below the reference level (0.8). The existence of the LED lamp without a dimmer in sub-scenarios B and D increases the uniformity factor above the reference level, and the possibility of uncomfortable glare is higher. In sub-scenarios C and E, where different glasses are used, and the LED lamp is dimmed, the uniformity factor is at the standard level throughout the day with the help of the control algorithms.

Ensuring lighting comfort for office workers is the first critical issue for managers. However, another problem is to reduce electricity consumption and, therefore, the electricity bill without compromising the comfort of the working area. Considering the daily energy consumption



```
Algorithm 1 Proposed Pseudocode for the LED Dimmer Adjustment Function
Function dimLED(measuredAverageLux, standardLux, measuredUniformityFactor, standardUniformity)
if measuredAverageLux == standardLux then
    return ledDimmer {Return current dimmer value if average lux matches standard level}
else if measuredAverageLux < standardLux then
    if measuredUniformityFactor < standardUniformity then
        ledDimmer -= DecreasePwmValue {Decrease dimming if average lux is high and uniformity is low}
    else
        ledDimmer -= DecreasePwmValue {Decrease dimming if average lux is high and uniformity is high}
    end if
else
    if measuredUniformityFactor < standardUniformity then
        ledDimmer += IncreasePwmValue {Increase dimming if average lux is low and uniformity is low}
    else
        ledDimmer += IncreasePwmValue {Increase dimming if average lux is low and uniformity is high}
    end if
end if
return ledDimmer {Return the adjusted dimmer value}
```

Fig. 5. Proposed pseudocode for LED dimmer adjustment in lighting control algorithm.



Algorithm 2 Proposed Pseudocode for the PDLC Dimmer Adjustment Function

```
Function PDLCDimmer(measuredAverageLux, standardLux, measuredUniformityFactor, standardUniformity)
if measuredAverageLux < standardLux then
    if measuredUniformityFactor < standardUniformity then
        pdlcDimmer += IncreasePwmValue {Increase dimming if average lux is below and uniformity is low}
    else
        pdlcDimmer += IncreasePwmValue {Increase dimming if average lux is below and uniformity is high}
    end if
else if measuredAverageLux == standardLux then
    Return pdlcDimmer {No change if average lux matches}
else
    if measuredUniformityFactor > standardUniformity then
        pdlcDimmer -= DecreasePwmValue {Decrease dimming if average lux is above and uniformity is high}
    else
        pdlcDimmer -= DecreasePwmValue {Decrease dimming if average lux is above and uniformity is low}
    end if
end if
return pdlcDimmer {Return the adjusted dimmer value}
```

Fig. 6. Proposed pseudocode for PDLC-based smart window in lighting control algorithm.

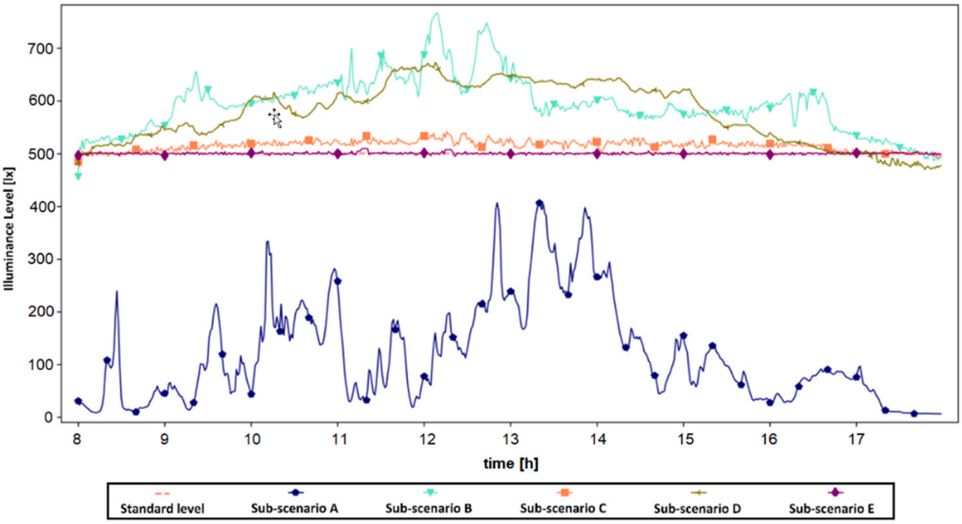


Fig. 7. Comparison of average illuminance curves.

shown in Fig. 9, sub-scenario A has no energy consumption since no LED lamps are used and only sunlight is utilized. The energy consumption in sub-scenarios B and D, where the LED lamp dimmer is not considered, is approximately equal to and relatively higher than the other sub-scenarios. The energy consumption decreases significantly in sub-scenario C, where the LED lamp can be dimmed, and in sub-scenario E, where the light transmittance is adjusted with the PDLC-based smart window in addition to the relevant dimmer. Reducing the light transmittance of the PDLC-based smart window affects the necessary uniformity factor, so the dimmer of the LED lamp has to be turned down completely. Therefore, the energy consumed in sub-scenario E is relatively higher than in sub-scenario C.

It is not enough to compare only energy consumption savings to assess whether an effective lighting method has been obtained. For the practicability of the control algorithm, lighting comfort and energy consumption must be related according to the dimmer levels. The relationship between dimmer percentage and lighting comfort is first shown in Fig. 10 the illuminance level peaks for all sub-scenarios, especially at noon. The illuminance level in Sub-scenario C is above the reference level even if the LED lamp is switched off at noon. On the contrary, even if the light transmittance of the PDLC-based smart window is low until 17.00 in Sub-scenario D, complete lighting comfort is not guaranteed as the illuminance level is above the reference. After 17.00, the light from the sun starts to decrease, and at the end of the day, the light transmittance of the PDLC-based smart window increases again. On the other hand, the illuminance level in Sub-scenario E is highest in the 11th and 12th hours. However, the reference illuminance level can be obtained by reducing the dimmer of the PDLC-based smart window after the LED dimmer is entirely dimmed. The LED dimmer level increases towards the end of the day as daylight decreases in the afternoon. Since the dimmer level of the PDLC-based smart window only decreases during the 11th and 12th hours, using it for the rest of the day is unnecessary.

Another viewpoint elaborates on the relationship between energy consumption and dimmer levels. As the dimmer level of the LED lamp decreases, energy consumption decreases in sub-scenarios C and E. The energy consumption is constant in sub-scenario D, where the LED lamp is operated without a dimmer. The relationship between energy

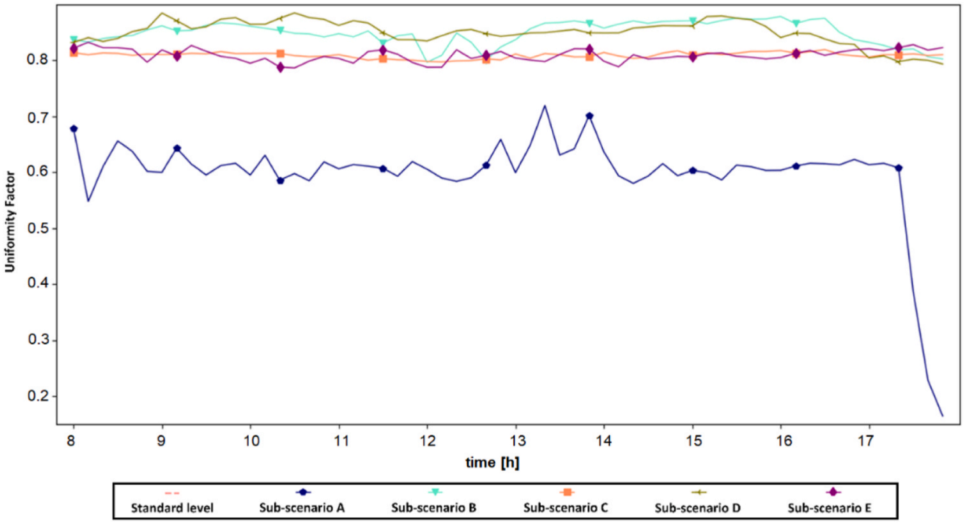


Fig. 8. Comparison of illumination uniformity factor curves.

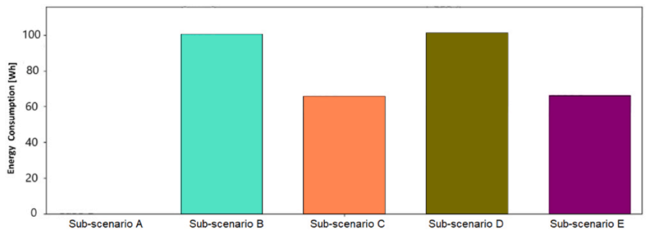


Fig. 9. Overview of office daily energy consumption for an example day (8:00–17:00).

consumption and dimming percentage is not evaluated in sub-scenario A, where the LED lamp is not used, and in sub-scenario B, where it is not dimmed even if used. Sub-scenario D is considered in the figures since the light transmittance of the PDLC-based smart window is adjusted by the dimmer or voltage level, even without dimmer control.

4. Discussion

The performance of scenario-based tests needs to be evaluated in highly variable weather conditions (Oh et al., 2019); this is our research's main shortcoming. It is mainly assessed by the variability approach (Wu et al., 2019). To achieve the relevant goal, the tinting of the split smart glass must be controlled according to the sky luminance distribution monitoring requirement, which is fulfilled by using an embedded photometric device. Moreover, a compact automation method based on real-time illumination calculation of the indoor area is planned. Several issues are debatable for changing weather conditions. Firstly, the sunlight from the window is responsible for most of the illuminance level within the test cell when the LED lamp operates in the off or near-off state. The difference between the illuminance levels becomes apparent when the sun shines at different angles in different parts of the room, in front of and behind the window. This difference causes the uniformity factor to decrease. Therefore, the lighting comfort requirements for the office area can be met by not compromising on energy savings or by not turning off the LED lamp entirely. To improve the decreasing uniformity factor of sub-scenario A in the evening hours, a window area can be designed for a large office. In this way, to allow solar radiation to spread into the room, an arch-like structure can be installed at the top of the window to block the sun from hitting in the evening hours. In addition to the control algorithms discussed in this study, the architectural structure of the building and the split window design should be utilized to adjust the uniformity factor according to the standards. (Han et al., 2023) and colleagues' work using the Radiance lighting simulation application is an example of such designs.

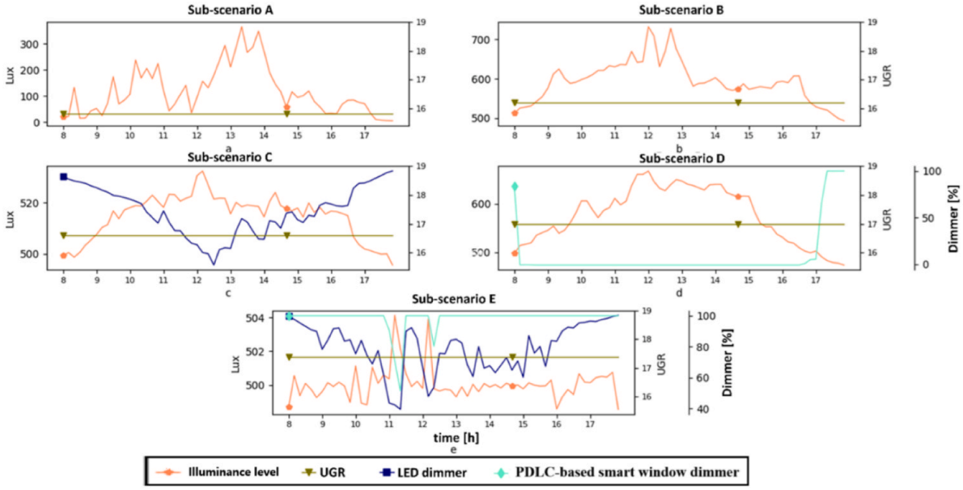


Fig. 10. Daily relationship of illuminance with percentage of dimmers.

On the other hand, the best feasible scenario considered in this study is to control both the light transmittance of the PDLC-based smart window and the LED lamp dimmer (Sub-scenario E). Energy savings are calculated considering Sub-Scenario B with uncontrolled LED and IG80 glass. The time interval and step are one year and one minute. Energy savings were determined by comparing the relative scenario's energy consumption with the best case. Energy savings increase by 22 % when the best scenario is chosen in an office area compared to using only LED lamps as an artificial light source. Original research in the literature focuses specifically on methods for energy consumption (see Table 5). The favorable result for energy consumption is very close to the findings in Table 5. This proves the competitiveness of the developed lighting control method. Also, as described in Table 1, lighting control methods are rarely considered to provide the desired level of visual comfort and reduce energy consumption in working areas. Instead, the focus is more on design parameters and technological advancement. This paper eliminates such efforts by proposing and developing control algorithms. Moreover, the dimmer relationships are considered to be one of the neglected issues by researchers. Therefore, providing fast and practical lighting solutions with lighting control methods confirms the method's superiority.

5. Conclusion

This study rigorously evaluates the performance of LED lamp dimmers and the PDLC-based smart window light transmittance control as the lighting control methods for visual comfort and energy consumption, considering an office model with IG80 glass as a reference. The results from the scenario-based test procedure, conducted with meticulous attention to detail, analyze the relationship of illuminance level, uniformity factor, and energy consumption with daily dimmer percentages. The test bench includes a sensor box, microcontroller, SD card, LED and the PDLC-based smart window drivers, auxiliary power circuit, and LED and the PDLC-based smart window. Control algorithms for the lighting method were developed in Python. The main objective of the experiments is to find the optimum lighting method that can provide a combination of lighting comfort and efficiency and, therefore, energy savings. The results prove that the optimal lighting management plan is the LED lamp dimmer and the PDLC-based smart window light transmittance control. At the same time, the method's viability is highly dependent on the weather and ambient conditions. It is also emphasized that in the existence of IG80 glass, LED lamp control without a dimmer and with a dimmer can serve a similar uniformity factor, and illuminance levels can be higher than in other scenarios. The energy consumption is reduced by up to 22 % by controlling the PDLC-based smart window light transmittance and LED dimmer to match the daylight and each other. Similar and competitive energy consumption performance was obtained with practical lighting control methods without dealing with design parameters and technological developments. It can be highlighted that it is optional to use smart glass in all cases for effective lighting control. Instead, managing the artificial light source is adequate depending on the in-room illuminance level. However, adjusting the light transmittance of the smart glass and the LED lamp dimmer control in rooms with high solar radiation potential is suggested. Moreover, similar technological advances in smart glass, which adjusts the light transmittance according to the voltage response, can be easily adapted to the control algorithm serving on lighting efficiency. In future studies, different options in smart glass will be evaluated, and other neglected aspects of the interior (heating and cooling load, energy consumption, ambient temperature, durability, and service life) will be considered in the lighting control algorithm to be developed. Instead of a test cell, experimental tests will be carried out at the indoor level without scaling, and inferences will be made for the neglected UDI index. Eventually, optimal management of lighting comfort and energy savings in future buildings can benefit governments in climate actions compared to renewable energy, enabling them to achieve adequate and clean energy goals and facilitate the transition to sustainable cities and societies.

Table 5
Comparison of the notable findings of the research with the results of the analysis.

Ref.	Notable numerical finding
(Park et al., 2019)	Lighting energy consumption was increased by 8.89 % by reducing visible light transmittance.
(Wu et al., 2023b)	UDI was increased to 79.88 % with the lighting strategy, resulting in 13.7 % energy savings.
(Han et al., 2023)	Up to 95.3 % of intolerable glare was avoided, and the UDI index of up to 73.3 % was achieved. Lighting energy consumption has been reduced by up to 29.8 %.
(Cannavale et al., 2018)	Energy savings of up to 25 % per year were achieved, and optimum lighting comfort was guaranteed for 82.7 % of the hours annually.
(Fathi and Kavoosi, 2021)	Combination with other equipment has reduced energy consumption by up to 35.6 %.
(Zhang et al., 2023)	UDI is improved by up to 75.3 % by design. Energy savings of up to 15.8 % compared to conventional glass.
(Li et al., 2023a)	Using a bleached technology means 39 % of daylight hours are glare-free, and lighting comfort is improved.
(Khatibi et al., 2022)	The hybrid control algorithm increased energy savings by up to 26.1 %, while energy efficiency was improved by 8.44 % compared to its constituent algorithms.
(Li et al., 2023b)	It guarantees energy savings of up to 19 % compared to single glass, with the option of color.
(Wu et al., 2019)	Even under rapidly changing daylight conditions, the variation in work plane illuminance and daylight glare probability was kept below 62 % and 85 %, respectively.
(Budaiwi and Abdul Fasi, 2023)	Thanks to the strategy, which utilizes daylight control but limits visual comfort, energy savings are increased by 23 % while visual comfort is not compromised.
This study	Thanks to the developed lighting control method, which includes the PDLC-based smart window and LED dimmer management, energy consumption has been reduced by 22 % compared to artificial light sources.

Ethics statement

The authors of the submitted paper declare that nothing necessary to achieve the paper requires the approval of an ethical committee and/or legal-special permissions.

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Author Statement

We confirm that the manuscript has been read and approved by all named authors and that there are no other persons who satisfied the criteria for authorship but are not listed. We further confirm that the order of authors listed in the manuscript has been approved by all of us.

CRediT authorship contribution statement

Hasan Gundogdu: Writing – original draft, Visualization, Software, Methodology, Investigation, Formal analysis, Data curation, Conceptualization. **Musa Terkes:** Writing – review & editing, Writing – original draft, Visualization, Resources, Methodology, Investigation, Conceptualization. **Alpaslan Demirci:** Writing – review & editing, Validation, Supervision, Methodology, Conceptualization. **Umit Cali:** Writing – review & editing, Validation, Supervision.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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Data Availability

The authors are unable or have chosen not to specify which data has been used.

References

Ahmed, A.E., Suwaed, M.S., Shakir, A.M., Ghareeb, A., 2023. The impact of window orientation, glazing, and window-to-wall ratio on the heating and cooling energy of an office building: the case of hot and semi-arid climate. J. Eng. Res. https://doi.org/10.1016/j.jer.2023.10.034.

Ajaji, Y., André, P., 2015. Thermal comfort and visual comfort in an office building equipped with smart electrochromic glazing: an experimental study. Energy Procedia 78, 2464–2469. https://doi.org/10.1016/j.egypro.2015.11.230.

Allen, K., Connelly, K., Rutherford, P., Wu, Y., 2017. Smart windows—dynamic control of building energy performance. Energy Build. 139, 535–546. https://doi.org/10.1016/j.enbuild.2016.12.093.

Arvizu, M.A., Granqvist, C.G., Niklasson, G.A., 2016. Rejuvenation of degraded electrochromic MoO3 thin films made by DC magnetron sputtering: Preliminary results. J. Phys. Conf. Ser. 764, 12009. https://doi.org/10.1088/1742-6596/764/1/012009.

Arvizu, M.A., Niklasson, G.A., Granqvist, C.G., 2017. Electrochromic W1–x–yTixMoyO3 thin films made by sputter deposition: large optical modulation, good cycling durability, and approximate color neutrality. Chem. Mater. 29, 2246–2253. https://doi.org/10.1021/acs.chemmater.6b05198.

Atak, G., Bayrak Pehlivan, I., Montero Amenedo, J., Granqvist, C.G., Niklasson, G., 2021a. Durability studies of annealed electrochromic tungsten oxide films. EMRS Fall Meet. 2021.

Atak, G., Bayrak Pehlivan, I., Montero Amenedo, J., Granqvist, C.G., Niklasson, G.A., 2021b. The role of oxygen to argon gas flow ratio on the durability of sputter-deposited electrochromic tungsten oxide films. EMRS Fall Meet. 2021.

Atangulova, A., Kochnov, A., Sennikova, A., 2024. Systems of automatic control of electrochromic devices, in: 2024. 6th International Youth Conference on Radio Electronics, Electrical and Power Engineering (REEPE). IEEE, pp. 1–6. https://doi.org/10.1109/REEPE60449.2024.10479767.

Bai, T., Li, W., Fu, G., Zhang, Q., Zhou, K., Wang, H., 2023. Dual-band electrochromic smart windows towards building energy conservation. Sol. Energy Mater. Sol. Cells 256, 112320. https://doi.org/10.1016/j.solmat.2023.112320.

Brzezicki, M., 2021. A systematic review of the most recent concepts in smart windows technologies with a focus on electrochromics. Sustainability 13, 9604. https://doi.org/10.3390/su13179604.

Budaiwi, I.M., Abdul Fasi, M., 2023. Assessing the energy-saving potential and visual comfort of electrochromic smart windows in office buildings: a case study in Dhahran, Saudi Arabia. Sustainability 15, 9632. https://doi.org/10.3390/su15129632.

Cannavale, A., Ayr, U., Fiorito, F., Martellotta, F., 2020. Smart electrochromic windows to enhance building energy efficiency and visual comfort. Energies 13, 1449. https://doi.org/10.3390/en13061449.

Cannavale, A., Martellotta, F., Cossari, P., Gigli, G., Ayr, U., 2018. Energy savings due to building integration of innovative solid-state electrochromic devices. Appl. Energy 225, 975–985. https://doi.org/10.1016/j.apenergy.2018.05.034.

Cardoso, M.A., Pereira, R.F.P., Pereira, S., Gonçalves, H., Silva, M.M., Carlos, L.D., Nunes, S.C., Fortunato, E., Ferreira, R.A.S., Rego, R., de Zea Bermudez, V., 2019. Three-mode modulation electrochromic device with high energy efficiency for windows of buildings located in continental climatic regions. Adv. Sustain. Syst. 3. https://doi.org/10.1002/adsu.201800115.

Costa, C., Ivanou, D., Pinto, J., Mendes, J., Mendes, A., 2019. Impact of the architecture of dye sensitized solar cell-powered electrochromic devices on their photovoltaic performance and the ability to color change. Sol. Energy 182, 22–28. https://doi.org/10.1016/j.solener.2019.02.036.

Detsi, M., Atsonios, I., Mandilaras, I., Founti, M., 2024. Effect of smart glazing with electrochromic and thermochromic layers on building's energy efficiency and cost. Energy Build. 319, 114553. https://doi.org/10.1016/j.enbuild.2024.114553.

Dussault, J.-M., Gosselin, L., 2017. Office buildings with electrochromic windows: a sensitivity analysis of design parameters on energy performance, and thermal and visual comfort. Energy Build. 153, 50–62. https://doi.org/10.1016/j.enbuild.2017.07.046.

Es-sakali, N., Idrissi Kaitouni, S., Ait Laasri, I., Oualid Mghazli, M., Cherkaoui, M., Pfafferott, J., 2024. Static and dynamic glazing integration for enhanced building efficiency and indoor comfort with thermochromic and electrochromic windows. Therm. Sci. Eng. Prog. 52, 102681. https://doi.org/10.1016/j.tsep.2024.102681.

Fathi, S., Kavoosi, A., 2021. Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. Sol. Energy 223, 132–149. https://doi.org/10.1016/j.solener.2021.05.021.

Gadgil, C., Ghosh, A., Bhattacharjee, A., Praveen, P.L., 2024. Electrically powered active smart windows. Sustain 3, 100027. https://doi.org/10.1016/j.nxsust.2024.100027.

Gago, E.J., Muneer, T., Knez, M., Köster, H., 2015. Natural light controls and guides in buildings. Energy saving for electrical lighting, reduction of cooling load. Renew. Sustain. Energy Rev. 41, 1–13. https://doi.org/10.1016/j.rser.2014.08.002.

Ghosh, A., Hafnaoui, R., Mesloub, A., Elkhayat, K., Albaqawy, G., Alnaim, M.M., Mayhoub, M.S., 2024. Active smart switchable glazing for smart city: A review. J. Build. Eng. 84, 108644. https://doi.org/10.1016/j.jobe.2024.108644.

Ghosh, A., Norton, B., Duffy, A., 2015. Measured overall heat transfer coefficient of a suspended particle device switchable glazing. Appl. Energy 159, 362–369. https://doi.org/10.1016/j.apenergy.2015.09.019.

Ghosh, A., Norton, B., Duffy, A., 2016b. Daylighting performance and glare calculation of a suspended particle device switchable glazing. Sol. Energy 132, 114–128. https://doi.org/10.1016/j.solener.2016.02.051.

Ghosh, A., Norton, B., Duffy, A., 2016a. Measured thermal performance of a combined suspended particle switchable device evacuated glazing. Appl. Energy 169, 469–480. https://doi.org/10.1016/j.apenergy.2016.02.031.

Ghosh, A., Norton, B., 2017. Interior colour rendering of daylight transmitted through a suspended particle device switchable glazing. Sol. Energy Mater. Sol. Cells 163, 218–223. https://doi.org/10.1016/j.solmat.2017.01.041.

Granqvist, C.G., Arvizu, M.A., Bayrak Pehlivan, İ., Qu, H.-Y., Wen, R.-T., Niklasson, G.A., 2018. Electrochromic materials and devices for energy efficiency and human comfort in buildings: a critical review. Electrochim. Acta 259, 1170–1182. https://doi.org/10.1016/j.electacta.2017.11.169.

Hafnaoui, R., mohd husini, E., zin Kandar, M., Ghosh, A., Mesloub, A., 2024. Smart switchable glazing systems in Saudi Arabia: a review. Energy Build. 319, 114555. https://doi.org/10.1016/j.enbuild.2024.114555.

Han, S., Sun, Y., Wang, W., Xu, W., Wei, W., 2023. Optimal design method for electrochromic window split-pane configuration to enhance building energy efficiency. Renew. Energy 219, 119405. https://doi.org/10.1016/j.renene.2023.119405.

Hoon Lee, J., Jeong, J., Tae Chae, Y., 2020. Optimal control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions. Appl. Energy 260, 114338. https://doi.org/10.1016/j.apenergy.2019.114338.

Hosseinzadeh Khaligh, H., Liew, K., Han, Y., Abukhdeir, N.M., Goldthorpe, I.A., 2015. Silver nanowire transparent electrodes for liquid crystal-based smart windows. Sol. Energy Mater. Sol. Cells 132, 337–341. https://doi.org/10.1016/j.solmat.2014.09.006.

Huang, J., Li, J., Xu, J., Wang, Z., Sheng, W., Li, H., Yang, Y., Song, W., 2019. Simultaneous achievement of high visible transmission and near-infrared heat shielding in flexible liquid crystal-based smart windows via electrode design. Sol. Energy 188, 857–864. https://doi.org/10.1016/j.solener.2019.06.063.

Jain, S., Karmann, C., Wienold, J., 2022. Behind electrochromic glazing: assessing user's perception of glare from the sun in a controlled environment. Energy Build. 256, 111738. https://doi.org/10.1016/j.enbuild.2021.111738.

Ji, Y.-X., Boman, M., Niklasson, G.A., Granqvist, C.-G., 2016. Thermochromics for energy-efficient buildings: thin surface coatings and nanoparticle composites. In: Pacheco Torgal, F., Buratti, C., Kalaiselvam, S., Granqvist, C.-G., Ivanov, V. (Eds.), Nano and Biotech Based Materials for Energy Building Efficiency. Springer International Publishing, Cham, pp. 71–96. https://doi.org/10.1007/978-3-319-27505-5_4.

Khatibi, A., Hossein Jahangir, M., Razi Astaraei, F., 2022. Energy and comfort evaluation of a novel hybrid control algorithm for smart electrochromic windows: a simulation study. Sol. Energy 241, 671–685. https://doi.org/10.1016/j.solener.2022.06.045.

Kim, J.-H., Hong, J., Han, S.-H., 2021. Optimized physical properties of electrochromic smart windows to reduce cooling and heating loads of office buildings. Sustainability 13, 1815. https://doi.org/10.3390/su13041815.

Ko, Y., Oh, H., Hong, H., Min, J., 2020. Energy consumption verification of SPD smart window, controllable according to solar radiation in South Korea. Energies 13, 5643. https://doi.org/10.3390/en13215643.

Lamontagne, B., Fong, N.R., Song, I.-H., Ma, P., Barrios, P.J., Poitras, D., 2019. Review of microshutters for switchable glass. J. Micro/Nanolithogr. MEMS, MOEMS 18, 40901. https://doi.org/10.1117/1.JMM.18.4.040901.

Lemarchand, P., Doran, J., Norton, B., 2014. Smart switchable technologies for glazing and photovoltaic applications. Energy Procedia 57, 1878–1887. https://doi.org/10.1016/j.egypro.2014.10.052.

Li, C., et al., 2020. An electrically light-transmittance-switchable film with a low driving voltage based on liquid crystal/polymer composites. Liq. Cryst. 47, 106–113. https://doi.org/10.1080/02678292.2019.1631969.

Li, Y., Li, Z., Chi, C., Shan, H., Zheng, L., Fang, Z., 2017. Plasmonics of 2D nanomaterials: properties and applications. Adv. Sci. 4, 1600430. https://doi.org/10.1002/advs.201600430.

Li, W., Shah, K.W., Li, Y., 2023a. Effects of electrochromic glass window on energy efficiency, thermal and visual performances under tropical climate. Energy Sustain. Dev. 76, 101300. https://doi.org/10.1016/j.esd.2023.101300.

Li, Y., Shah, K.W., Li, W., Xiong, T., 2023b. Experimental investigation on indoor thermal environment improvement and energy-saving of electrochromic window under Singapore's tropical climate. J. Build. Eng. 73, 106779. https://doi.org/10.1016/j.jobe.2023.106779.

Li, Z., Wu, Z., 2024. A study on the impact of electrochromic glazing on indoor environment. J. Build. Eng. 86, 108684. https://doi.org/10.1016/j.jobe.2024.108684.

Malekafzali Ardakan, A., Sok, E., Niemasz, J., 2017. Electrochromic glass vs. fritted glass: an analysis of glare control performance. Energy Procedia 122, 343–348. https://doi.org/10.1016/j.egypro.2017.07.334.

Mardare, C.C., Hassel, A.W., 2019. Review on the versatility of tungsten oxide coatings. Phys. Status Solidi 216. https://doi.org/10.1002/pssa.201900047.

Martín-Chivelet, N., Guillén, C., Trigo, J.F., Herrero, J., Pérez, J.J., Chenlo, F., 2018. Comparative performance of semi-transparent PV modules and electrochromic windows for improving energy efficiency in buildings. Energies 11, 1526. https://doi.org/10.3390/en11061526.

Meng, X, et al., 2021. Polymer dispersed liquid crystals doped with low concentration γ-Fe2O3 nanoparticles. Liq. Cryst. 48, 1791–1805. https://doi.org/10.1080/02678292.2020.1852620.

Michael, M., Favoino, F., Jin, Q., Luna-Navarro, A., Overend, M., 2023. A systematic review and classification of glazing technologies for building façades. Energies 16, 5357. https://doi.org/10.3390/en16145357.

Morales-Luna, M., Arvizu, M.A., Granqvist, C.G., Niklasson, G.A., 2016. Electrochromic properties of W1—Ni Ti O3 thin films made by DC magnetron sputtering. Thin Solid Films 615, 292–299. https://doi.org/10.1016/j.tsf.2016.06.058.

Ni, D., Cheng, D., Liu, Y., Wang, X., Yao, C., Yang, T., Chi, C., Wang, Y., 2022. Uniformity improvement of two-dimensional surface relief grating waveguide display using particle swarm optimization. Opt. Express 30, 24523. https://doi.org/10.1364/OE.462384.

Nundy, S., Ghosh, A., 2020. Thermal and visual comfort analysis of adaptive vacuum integrated switchable suspended particle device window for temperate climate. Renew. Energy 156, 1361–1372. https://doi.org/10.1016/j.renene.2019.12.004.

Nundy, S., Mesloub, A., Alsolami, B.M., Ghosh, A., 2021. Electrically actuated visible and near-infrared regulating switchable smart window for energy positive building: a review. J. Clean. Prod. 301, 126854. https://doi.org/10.1016/j.jclepro.2021.126854.

Oh, M., Jang, M., Moon, J., Roh, S., 2019. Evaluation of building energy and daylight performance of electrochromic glazing for optimal control in three different climate zones. Sustainability 11, 287. https://doi.org/10.3390/su11010287.

Papathanasopoulos, D., Leftheriotis, G., Mitronikas, E., 2017. Design, fabrication, and testing of an electronic device for the automatic control of electrochromic windows. J. Build. Eng. 12, 248–258. https://doi.org/10.1016/j.jobe.2017.06.012.

Park, B.R., Hong, J., Choi, E.J., Choi, Y.J., Lee, C., Moon, J.W., 2019. Improvement in energy performance of building envelope incorporating electrochromic windows (ECWs). Energies 12, 1181. https://doi.org/10.3390/en12061181.

Shen, W., Li, G., 2023. Recent progress in liquid crystal-based smart windows: materials, structures, and design. Laser Photonics Rev. 17, 2200207. https://doi.org/10.1002/lpor.202200207.

Soares, I.T., de Araújo, J.R., Monteiro, S.N., Marques, M., de, F.V., 2023. Novel system using hydrogel with reduced graphite oxide particles as active layer for potential application in smart window. J. Mater. Res. Technol. 22, 1924–1934. https://doi.org/10.1016/j.jmrt.2022.12.057.

Suzuki, E.H., Lofrano, F.C., Kurokawa, F.A., Prado, R.T.A., Leite, B.C.C., 2022. Decision-making process for thermal comfort and energy efficiency optimization coupling smart-window and natural ventilation in the warm and hot climates. Energy Build. 266, 112110. https://doi.org/10.1016/j.enbuild.2022.112110.

Tällberg, R., Jelle, B.P., Loonen, R., Gao, T., Hamdy, M., 2019. Comparison of the energy saving potential of adaptive and controllable smart windows: a state-of-the-art review and simulation studies of thermochromic, photochromic and electrochromic technologies. Sol. Energy Mater. Sol. Cells 200, 109828. https://doi.org/10.1016/j.solmat.2019.02.041.

Triana, C.A., Granqvist, C.G., Niklasson, G.A., 2015. Electrochromism and small-polaron hopping in oxygen deficient and lithium intercalated amorphous tungsten oxide films. J. Appl. Phys. 118, 24901. https://doi.org/10.1063/1.4926488.

Villa, D.L., Hahn, N.T., Grey, J.K., Pavich, F., 2024. Futures for electrochromic windows on high performance houses in arid, cold climates. Energy Build. 315, 114293. https://doi.org/10.1016/j.enbuild.2024.114293.

Wang, Y., Runnerstrom, E.L., Milliron, D.J., 2016. Switchable materials for smart windows. Annu. Rev. Chem. Biomol. Eng. 7, 283–304.

Wen, Rui-Tao, Arvizu, M.A., Morales-Luna, M., Granqvist, C.G., Niklasson, G.A., 2016a. Ion trapping and detrapping in amorphous tungsten oxide thin films observed by real-time electro-optical monitoring. Chem. Mater. 28, 4670–4676. https://doi.org/10.1021/acs.chemmater.6b01503.

Wen, R.-T., Arvizu, M.A., Niklasson, G.A., Granqvist, C.G., 2016. Electrochromics for energy efficient buildings: towards long-term durability and materials rejuvenation. Surf. Coat. Technol. 290, 135–139. https://doi.org/10.1016/j.surfcoat.2016.02.031.

Wen, R.-T., Granqvist, C.G., Niklasson, G.A., 2015. Eliminating degradation and uncovering ion-trapping dynamics in electrochromic WO3 thin films. Nat. Mater. 14, 996–1001. https://doi.org/10.1038/nmat4368.

Wen, Rui-Tao, Niklasson, G.A., Granqvist, C.G., 2016b. Eliminating electrochromic degradation in amorphous TiO2 through Li-ion detrapping. ACS Appl. Mater. Interfaces 8, 5777–5782. https://doi.org/10.1021/acsami.6b00457.

Wikipedia,n.d. Smart glass [WWW Document].

Wu, S., Sun, H., Duan, M., Mao, H., Wu, Y., Zhao, H., Lin, B., 2023a. Applications of thermochromic and electrochromic smart windows: materials to buildings. Cell Rep. Phys. Sci. 4, 101370. https://doi.org/10.1016/j.xcrp.2023.101370.

Wu, Y., Wang, T., Lee, E.S., Kämpf, J.H., Scartezzini, J.-L., 2019. Split-pane electrochromic window control based on an embedded photometric device with real-time daylighting computing. Build. Environ. 161, 106229. https://doi.org/10.1016/j.buildenv.2019.106229.

Wu, X., Zhang, W., Xie, L., Zhao, O., Li, Z., Li, J., Zhong, J., 2023b. Study on the impact of partition photovoltaic electrochromic windows on building lighting environment and energy saving. Energy Build. 280, 112722. https://doi.org/10.1016/j.enbuild.2022.112722.

Zhang, H., Miao, Z., Shen, W., 2022. Development of polymer-dispersed liquid crystals: From mode innovation to applications. Compos. Part A Appl. Sci. Manuf. 163, 107234. https://doi.org/10.1016/j.compositesa.2022.107234.

Zhang, W., Wu, X., Xie, L., Zhao, O., Zhong, J., Zeng, X., Zou, R., 2023. Study on the impact of photovoltaic electrochromic modular smart window on indoor environment. Build. Environ. 238, 110381. https://doi.org/10.1016/j.buildenv.2023.110381.

Zhao, S., Wang, B., Zhu, N., Huang, Y., Wang, F., Li, R., Zhao, Y., Jiang, Q., Wu, X., Zhang, R., 2023. Dual-band electrochromic materials for energy-saving smart windows. Carbon Neutralization 2, 4–27. https://doi.org/10.1002/cnl2.38.

Zhao, Z., Zhang, H., Zheng, H., Liu, S., 2018. New reversing freeform lens design method for LED uniform illumination with extended source and near field. Opt. Commun. 410, 123–129. https://doi.org/10.1016/j.optcom.2017.09.101.