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Assessing the Energy-Saving Potential and Visual Comfort of Electrochromic Smart Windows in Office Buildings: A Case Study in Dhahran, Saudi Arabia

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Abstract: This study comprehensively evaluates the energy-saving potential and visual comfort aspects of electrochromic (EC) smart windows in a hot-humid climate office building. Using an advanced building simulation tool, EC windows are compared to conventional low-E glazed windows, considering two control triggers: daylighting level and glare control. The primary objective is to determine energy savings achievable with EC windows while addressing visual comfort. Detailed analysis of the building's energy performance and indoor environment is conducted. Results show significant energy savings of 23% with EC windows using daylighting control but limited visual comfort in some zones. Conversely, EC windows with glare control achieve 17% energy savings while maintaining visual comfort throughout the building. These findings highlight the potential of EC windows with glare control in saving energy and maintaining visual comfort in hot-humid office buildings. Further research is needed to optimize performance for different building types and climates. In conclusion, this study provides insights into energy-saving capabilities and visual comfort considerations with EC smart windows, emphasizing the importance of appropriate control triggers for maximizing energy savings and occupant comfort. Future investigations should explore EC window performance across diverse building typologies and climates to enhance the benefits of this innovative technology.

Keywords: energy saving; daylighting; visual comfort; glare; office building; windows; electrochromic smart windows

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1. Introduction

1.1. An Overview on Smart Windows

The building envelope serves as a crucial interface between the indoor and outdoor environments. It regulates the interior temperature and plays a significant role in determining the energy required to maintain thermal comfort. Minimizing heat transfer through the building envelope is essential for reducing the need for space heating and cooling (Rawat & Singh, 2022) [1]. The transmission of solar radiation through windows is a significant energy flow through many commercial building envelopes, which can significantly inflate building cooling loads (Kini, Garg, & Kamath, 2022) [2]. However, proper selection of window glazing and effective lighting control strategy with daylight provision can be used to offset electric requirements and cooling requirements (Fasi & Budaiwi, 2015) [3]. Recent technological advancements in the field of windows and daylighting controls have led to significant improvements in energy savings in buildings. Smart windows, in particular, are made of materials that can be easily switched between a transparent state and a state that is opaque, translucent, and reflective. The switching is done by applying an electric voltage to the material, and they can be used to regulate the flow of light and radiant heat into or out of a building or other space (Nguyen, et al., 2020) [4]. Photochromic, thermochromics, suspended particle device, and electrochromic (EC) windows are some of the different types of smart windows that are available for lab experiments and commercial use. Among these, EC smart windows are considered the most reliable and are used in this study to examine their potential in energy savings and visual comfort in an office building (Mesloub, et al., 2022) [5].

Aldawoud conducted a study on the performance of electrochromic glazing in mitigating solar heat gains in a typical office building situated in a hot-humid climate. The office building was modeled using the DesignBuilder software and the simulation process involved varying the window shading conditions and glazing types. The results of Aldawoud's study demonstrate that EC glazing outperforms other tested shading conditions in reducing solar heat gains (Aldawoud, 2013) [6]. Myunghwan et al. assessed the performance of buildings in terms of energy consumption and daylight utilization and proposed the recommendations that would enhance the overall efficiency and effectiveness of EC glass applications in building environments (Oh, Jang, Moon, & Roh, 2019) [7]. Li et al. investigated the thermal performance of double-glazed EC glass windows in the tropical climate conditions of Singapore. The investigation results revealed that, during sunny outdoor weather conditions, the EC window glass demonstrated notable improvements by improving the indoor thermal environment and air conditioning energy savings (Li, Shah, Li, & Xiong, 2023) [8]. Alqalami conducted a study that yielded significant insights regarding the impact of smart glazing materials on the enhancement of thermal comfort in response to varying climate conditions inside the buildings. The study's findings unequivocally demonstrate the capacity of smart glazing materials to effectively restore and maintain optimal thermal comfort levels (Alqalami, 2020) [9]. Sarmadi et al. reached a conclusive finding in their research study, affirming that EC low-E glass windows offer the most optimal design patterns for integrating microalgae into curtain wall windows of office buildings (Sarmadi & Mahdavinejad, 2023) [10]. Ghosh et al. conducted an investigation on the visual comfort performance of semitransparent Perovskite Building Integrated Photovoltaic (BIPV) windows in an office building situated in Riyadh, Kingdom of Saudi Arabia (KSA). Their study focused on evaluating visual comfort through daylight glare analysis, considering the specific context of the office building (Ghosh, Mesloub, Touahmia, & Ajmi, 2021) [11].

The growing awareness about energy conservation and the rising demand for green building solutions is widely considered as the key drivers for the growth of the EC smart glass market. EC smart glass is a sustainable option and helps in reducing the building energy consumption and improving the indoor environment by reducing glare and providing natural light. This can lead to increased productivity, reduced stress, and improved employee satisfaction. EC smart coating is applied on the surface of the glass panels. The coating is made of a material that changes its color when an electric current is applied. This allows EC glass to be tuned to various states, from opaque to transparent, allowing users to control the amount of light and heat that enters a building (Casini, 2018) [12]. EC glass needs a low-voltage direct current power supply to operate and has very low power consumption. It can be operated in temperatures ranging from −20 °C to 80 °C, making it a versatile option for use in a variety of climates. EC glass can block over 99% of ultraviolet radiation, thereby protecting people and objects from the harmful effects of UV radiation. EC glass has a lifespan of over 20 years, making it a more sustainable option than other types of smart glass (Nundy, Mesloub, Alsolami, & Ghosh, 2021) [13]. The coating of EC smart glass consists of five layers, about 1 micron thick, and is deposited on the glass substrate. The EC stack consists of thin metallic coatings of nickel or tungsten oxide sandwiched between two transparent electrical conductors. When voltage is applied between the transparent electrical conductors, a distributed electrical field is set up. This field moves various coloration ions reversibly between the ion storage film through the ion conductor and into the EC film. The effect is that the glazing switches between a clear and transparent and a tinted state. They require low voltage power (0–10 volts DC) and remain transparent across their switching range. They have a unique feature of changing the optical and thermal properties of glass due to their chemical composition (Rakibuddin, Shinde, & Kim, 2020) [14]. Based on a given set of control triggers, EC glass can result in more optimal operation of glass and thus result in more overall energy savings (Prakash, 2012) [15]. In this research study, two control triggers were examined—daylighting level and glare control—to evaluate their impact on energy savings and visual comfort in an office building model located in a hot-humid climate of Dhahran. The characteristics of EC smart windows for both the ON and OFF states are shown in Table 1.

Table 1. Thermal and visual characteristics of EC smart windows.

State of Glass	Visible Transmission (%)	Solar Transmission (%)	Solar Heat Gain Coefficient	U-Value (W/m^2-K)
ON State (Bleached)	75	64	0.73	2.4
OFF State (Colored)	13	11	0.11	

Through an extensive literature review in the specific technical field disclosed in this paper, the authors discovered a significant research gap. They found a lack of research studies evaluating the performance of controllers used to regulate the phase change of EC glazing. Furthermore, no research study was found that assessed the visual comfort experienced by users when utilizing EC glass as glazing in the windows, as opposed to conventional glass windows. Addressing these gaps in knowledge, the present research study aims to fill this void by investigating the performance of the controller and evaluating the visual comfort aspects of EC glazing in comparison to conventional glass windows.

1.2. Control Strategies for Activating Electrochromic (EC) Smart Windows in Buildings

EC smart windows are a type of glass that can alter their transparency in response to an applied electric voltage. The window's transparency is managed by a control mechanism that is programmed to respond to various control triggers based on the exterior or interior conditions of the building (Piccolo & Simone, 2015) [16]. The exterior control triggers include solar incidence on the glazing, while interior triggers include the daylighting level and glare index at the daylight sensor. For example, daylighting illumination is a valid control trigger for EC glass, and daylighting sensors are used to adjust the transmittance of the glazing to meet the required daylight illuminance set point. If the total daylight glare index exceeds the maximum glare index specified in the daylighting input for the zone, shading is turned ON. Similarly, if the beam plus diffuse solar radiation incident on the window exceeds the set point radiation level, shading is also turned ON. Designers can specify different radiation set point levels for different orientations to optimize the integration of daylight.

The controller of the EC smart glass adjusts the properties of the window glass based on these control triggers. An artificial daylight sensor placed on the ceiling measures the daylight coming from the EC glass window and sends a signal to reduce the fractional input power of artificial lighting in discrete steps.

1.3. Scope of Research

The aim of this research is to evaluate the influence of EC glass windows on the cooling energy and lighting energy usage in an office building, while taking into account the integration of both daylight and artificial light. The research employs the DesignBuilder software tool to model and analyze an office building, using the design characteristics commonly employed in Dhahran, Saudi Arabia. The simulation is conducted using Dhahran weather data, and a comparison is made between the energy savings and visual comfort of buildings with EC glass windows and those with conventional low-E glass windows. Additionally, the payback period is calculated based on the energy savings and visual comfort. This research study examines two control triggers for EC windows (daylight control, glare control) and assesses their effectiveness in maintaining visual comfort and reducing energy consumption.

2. Building Simulation Software for Measuring the Energy Savings and the Visual Comfort Analysis

Building energy simulation tools are crucial in studying the energy usage of buildings. The DesignBuilder software was chosen for the energy analysis for this study due to its ability to quickly model complex buildings. The DesignBuilder software utilizes the latest energy plus simulation engine to compute the building's energy performance. Additionally, the software's daylighting module calculates the interior daylighting illuminance, glare from windows, glare control, and electric lighting controls [17,18].

2.1. Daylight and Glare Index Calculations Using the DesignBuilder Software

DesignBuilder software offers daylighting simulations that enable users to calculate daylight factors and illuminance data using the widely respected radiance daylight simulation engine. These simulations take into account building geometry, zone layouts, surface reflection, and glazing visible transmission properties from the thermal model. The tool's daylighting model, combined with the thermal analysis, determines the energy impact of daylighting strategies based on daylight availability, site conditions, window management, and lighting control strategies to reduce energy consumption (Kang & Kim, 2021) [19]. The software calculates daylight discomfort glare at a reference point due to luminance contrast between a window and surrounding interior surfaces. The software tool divides the window into small rectangular elements to calculate interior illuminance levels in a day-lit zone that has windows (Ahmad, Kumar, Prakash, & Aman, 2020) [20].

2.2. Artificial Lighting Integration with Daylighting Using the DesignBuilder Software

Integrating natural daylight with lighting control is considered a crucial strategy for energy-efficient building designs and operations. DesignBuilder's lighting control is adjusted based on the availability of natural daylight. When the lighting control is switched ON, illuminance levels are measured and used to determine the electric lighting reduction. Daylight illuminance is influenced by various factors, including sky condition, sun position, photocell sensor location, window size and transmittance, and reflectance of interior surfaces. Reduction of electric lighting depends on daylight illuminance, illuminance set point, and type of lighting control (Bhattacharya, Majumder, Roy, & Sardar, 2022) [21]. In this study, each zone was equipped with two lighting sensors, controlling different percentages of the lighting area. Stepped lighting control was used to integrate natural daylight with artificial lighting, allowing for discrete steps in electric power input and light output. This simplified mechanism can be useful for estimating the upper limits of potential savings through natural daylight integration.

3. Creation of a Base Case Model for an Office Building

By conducting a comprehensive literature review and survey analysis, this study examined and analyzed the design features of office buildings situated in the hot and humid climate of Dhahran. The collected information was utilized to identify the prevailing building characteristics, which were subsequently employed to develop a representative model of a typical office building in this region. The findings revealed that office buildings in Dhahran exhibit an average floor area ranging from 300 m^2 to 800 m^2, with a rectangular shape being the prevailing plan layout. These findings provide valuable insights into the typical size and configuration of office buildings in the specific context of Dhahran's hot and humid climate, thereby enhancing our understanding of the local building practices (AL-ASHWAL, 2009) [22]. The modeled building was assumed to have 11 floors, including the ground and roof floors, with the same office function throughout. Each floor was divided into 9 zones to account for the 7m detection range of each daylight sensor, with

2 sensors placed in each zone. The first sensor controlled 70% of the artificial lighting area for that zone, while the second sensor controlled the remaining 30%. The floor plan and location of the daylight sensors are shown in Figure 1, and the physical and thermal properties of the exterior wall, roof, and ground floor are detailed in Table 2. The roof design was based on ASHRAE Handbook-Roof 16 (AL-ASHWAL, 2009) [22]. No sensor was placed in the core zone due to the low availability of daylight in that area.

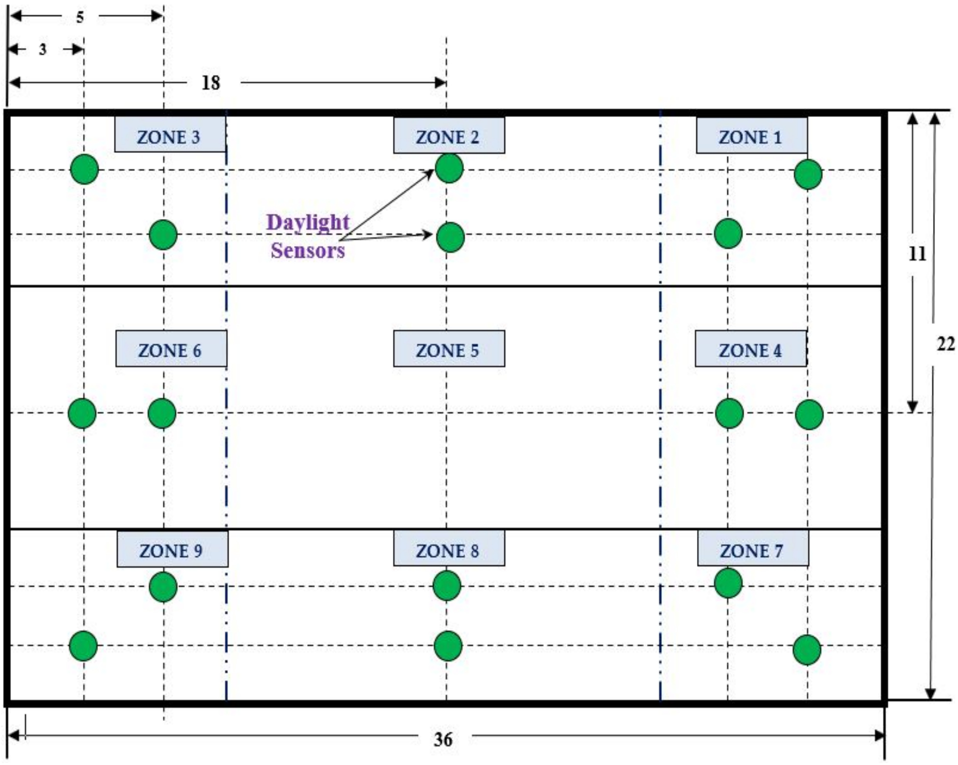

Figure 1. Office building base case plan with location of daylight sensors for different zones.

Table 2. Physical properties of the exterior wall, roof, and ground floor of office building model.

Construction Assembly	Elements from Outside to Inside	Thermal Conductivity (λ) (W/m-K)	U-Value (W/m^2-K)
Wall Cross section	Stone cladding	2.900	0.740
	Air gap	0.300	
	Expanded polystyrene	0.040	
	Lightweight concrete	0.170	
	Plaster board	0.250	
Roof Cross section	Built-up roofing	0.160	0.303
	Fiberboard sheathing	0.060	
	R-15, Insulation board	0.035	
	Lightweight concrete	0.170	
Floor Cross section	Flooring	0.140	0.509
	Floor screed	0.410	
	Cast concrete	1.130	
	Foam	0.040	

Windows with low-E glass were chosen for this study because the tinted coating on low-E blocks a considerable percentage of the sun's heat, reducing the load on the air conditioner. The film may help preserve the furnishings from fading and reduce glare, making some spaces considerably more pleasant (Somasundaram, Chong, Wei, & Thangavelu, 2020) [23]. In all orientations, the window-to-wall ratio (WWR) was considered to be 50%. The windowsill was set at 0.9 m per standard practice. Variable air volume (VAV) was chosen for cooling the zones around the perimeter, whereas constant air volume was chosen for the core zone because it was found to be effective in hot climates. VAV systems can reduce power consumption significantly, especially in peripheral zones where changes in solar load and outdoor temperature allow for lower air flow rates (Lu & Warsinger, 2020) [24]. The supply temperature at the diffuser was set at 14 °C, while the interior cooling design temperature was set at 24 °C, in accordance with ASHRAE standards. It was also assumed that grid electricity was used to generate cooling energy. Mechanical ventilation was selected based on energy standards, which vary depending on the number of people and the area to be ventilated for each zone (Amai & Novoselac, 2016) [25]. The simulations conducted in this research study utilized weather data that represent the prevailing climatic conditions of Dhahran which represent the hot-humid climate. This weather data incorporate hourly solar radiation and meteorological factors, spanning a period of one year, and were obtained from the archives of the 1985-2010 Climate Data Base for Saudi Arabia (Knoema) [26]. Table 3 presents the internally designed conditions for the base case model of the office building.

Table 3. Internal design conditions of the base case model of the office building.

Internal Conditions of the Office Building	Values
Perimeter zone illumination	500 Lux (IESNA, 10th Edition Handbook, 2011) [27]
Core zone illumination	300 Lux (Sanjog, Patel, & Karmakar, 2013) [28]
Lighting type	Triphosphor Fluorescent lamps
Illumination power density	2.4 W/m^2-100 Lux (ASHRAE 90.1-2019)
Equipment power density	5 W/m^2 (ASHRAE 90.1-2019)
Luminaire type	Recessed into the ceiling (Dilaura, Houser, Mistrick, & Steffy, 2011) [27]
Building Operation and Occupancy Schedule Consistency	Consistent throughout summer and winter seasons
Daily schedule	Start: 6:00 AM, End: 6:00 PM, Lunch: 12:00–13:00 (based on logical judgment and common practice)
System operation on holidays	Lighting and HVAC systems turned off
System operation on Fridays	Lighting and HVAC systems turned off

4. Results

4.1. Office Building Base Case Model Verification

Once the base case model was created in the DesignBuilder software, the model was used to examine the energy savings and visual comfort performance in all the zones. The simulation results, which included lighting and cooling energy consumption, were analyzed and compared to available energy data from an actual building. Based on the calculations made by the software, the annual electric energy consumption for the base case modeled was estimated to be roughly 2,572,450 kWh (308 kWh/m^2/Year). The annual energy consumption breakdown for the building model revealed that 67% of the total energy was used for cooling all the zones of the building, 15% for running the artificial lighting, and 18% for running all the equipment in the building. Figure 2 shows the lighting, cooling, and total consumption of energy in the modeled building over the course of a year. Energy consumption rises during the summer months (from April to August) due to higher cooling load requirements but falls during the winter months (from September to March) due to the decrease in the cooling demand caused by changes in outside weather conditions. The tinted coating on the low-E glass keeps solar radiation out in warmer places, resulting in the reduction in cooling energy consumption. The coating absorbs heat from the exterior environment, lowering the solar gain and cooling costs. Because the lighting energy requirement remains constant throughout the year, as a result we see a straight-line trend in the lighting energy consumption in Figure 2.

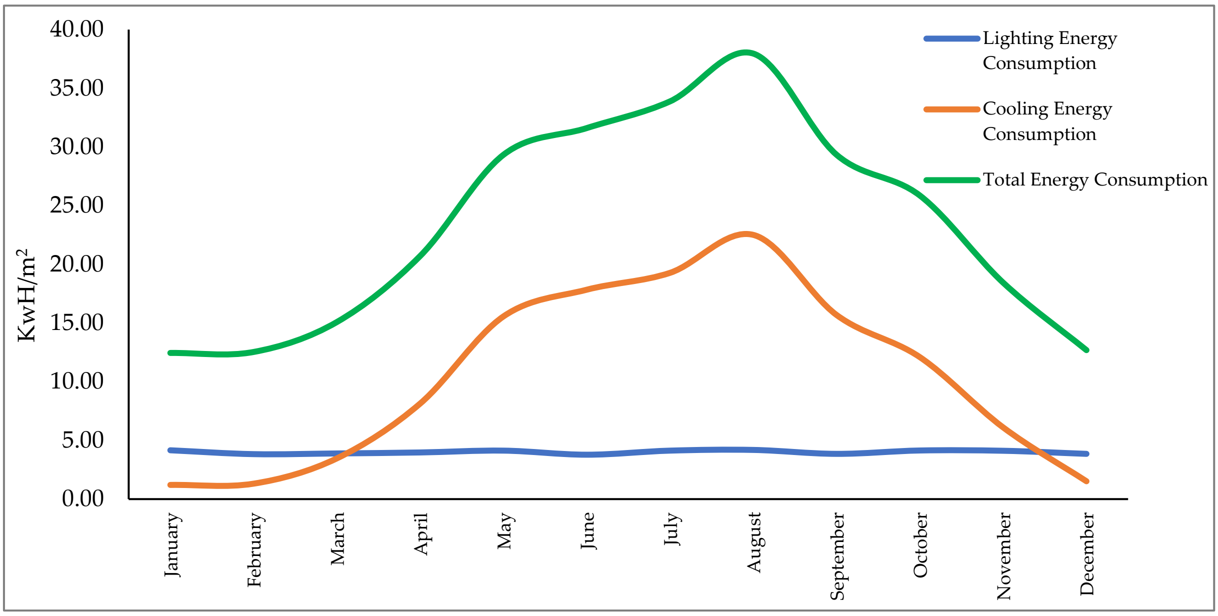

Figure 2. Electrical Energy Consumption for the modeled building over a period of one year.

The simulated building model was validated by comparing its energy performance to that of a real building located in the hot-humid region of Dhahran. The real building structure chosen for comparison is an office building located in the Eastern Province region, Dhahran city, Saudi Arabia, with a hot and humid climate (AL-ASHWAL, 2009) [22]. The real building structure is square in design, with the entrance facing east (30 m length × 30 m breadth × 41 m height). The real building comprises nine floors, each with the same office purpose. In accordance with the building plan, the total floor area of the building is 8400 m^2. Each level is 862 m^2 in size, and the majority of the real building's attributes have been found to be similar to the base case model created in the DesignBuilder software. Utility bills from the real office building were received from building management in order to compare the monthly energy consumption data of the simulated building model with the actual building. Table 4 presents a comprehensive comparison between the energy performance of the simulated base case building model and the actual office building. The analysis aimed to assess the accuracy and reliability of the simulated model by evaluating its energy consumption in relation to the real building. The results exhibited a minimal discrepancy of only 2.7% between the electrical consumption of the actual building and the energy consumption of the base case modeled building. This close alignment between simulated and real office building energy consumption substantiates the validity and robustness of the model for conducting further investigations into energy conservation measures. The findings instill confidence in the model's ability to accurately simulate and evaluate the effectiveness of various energy-saving strategies within the context of the office building, providing a valuable tool for informed decision making and performance optimization in the realm of sustainable building design and operation.

Table 4. Energy consumption end-use comparison for base case and existing building.

Type of Building	Energy End-Use				Energy Signature (KwH/m^2/Year)
	Cooling (%)	Lighting (%)	Fans (%)	Others (%)	
Real Building	45	15	22	18	317
Base Case Modeled (Simulated)	52	14	24	10	308

4.2. Evaluation of Energy Performance with Low-E Glass Facades and Daylight Integration

The lighting control sensor in the DesignBuilder will measure the available daylight for each zone and send a signal to the artificial lighting system to dim down to the prescribed illumination level. Lighting levels are measured at each time step of the simulation and are utilized to calculate how much electric lighting was reduced. In this study, a stepped lighting control mechanism was used to reduce artificial lighting after transmitting daylight from outside. Figure 3 represents the proposed fraction of lights that will remain on at various reduced illumination levels. By turning on the stepped lighting control for the modeled building, simulations were carried out. The integration of daylight and artificial lighting results in the following:

- Reduction in the lighting consumption of the modeled building by 66%;
- Reduction in the cooling energy consumption by 9%;
- Reduction in total building energy consumption by 16%.

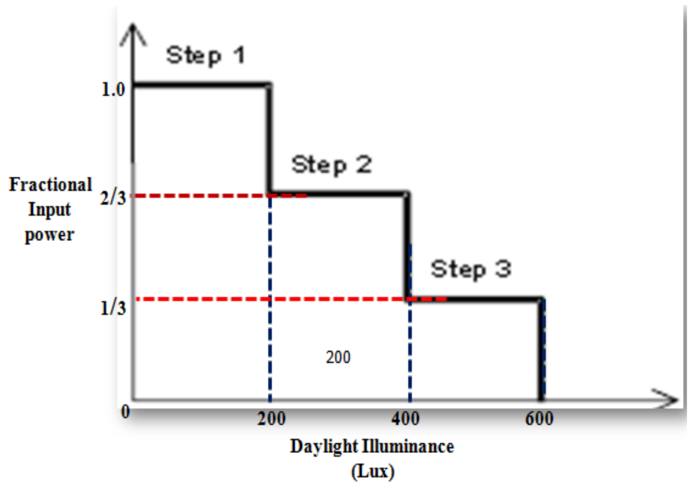

Figure 3. Stepped lighting control mechanism with different illumination levels.

Figure 4 provides a comparative analysis of monthly energy consumption, both prior to and following the integration of daylighting. The implementation of daylighting techniques resulted in a substantial influx of natural light, leading to a remarkable reduction in the electrical consumption associated with lighting. The data presented in Figure 4 underscore the significant energy savings achieved through the effective utilization of daylighting principles (Fasi & Budaiwi, 2015) [3]. Stepped lighting control reduces artificial lighting energy usage by minimizing the power input to the luminaries to balance the illumination level inside the office area. Low-E coatings have an emittance as low as 0.04 and emit only 4% of the energy possible at their temperature while reflecting 96% of incident long-wave infrared light. By lowering the emittance of the glass, the solar gain from outside is reduced, lowering the cooling load in the building. The data shown in Figure 4 reveals an important aspect of this research study, namely the impact of stepped control in minimizing the heat released by internal lighting sources within the building. Through the dimming effect enabled by the stepped control system, the heat generated by the lighting sources is significantly reduced. Consequently, this reduction in internal heat gain translates into a notable decrease in the cooling load imposed on the building over the course of several months. This emphasizes the effectiveness of daylighting in mitigating heat-related challenges and optimizing the overall thermal performance of the building.

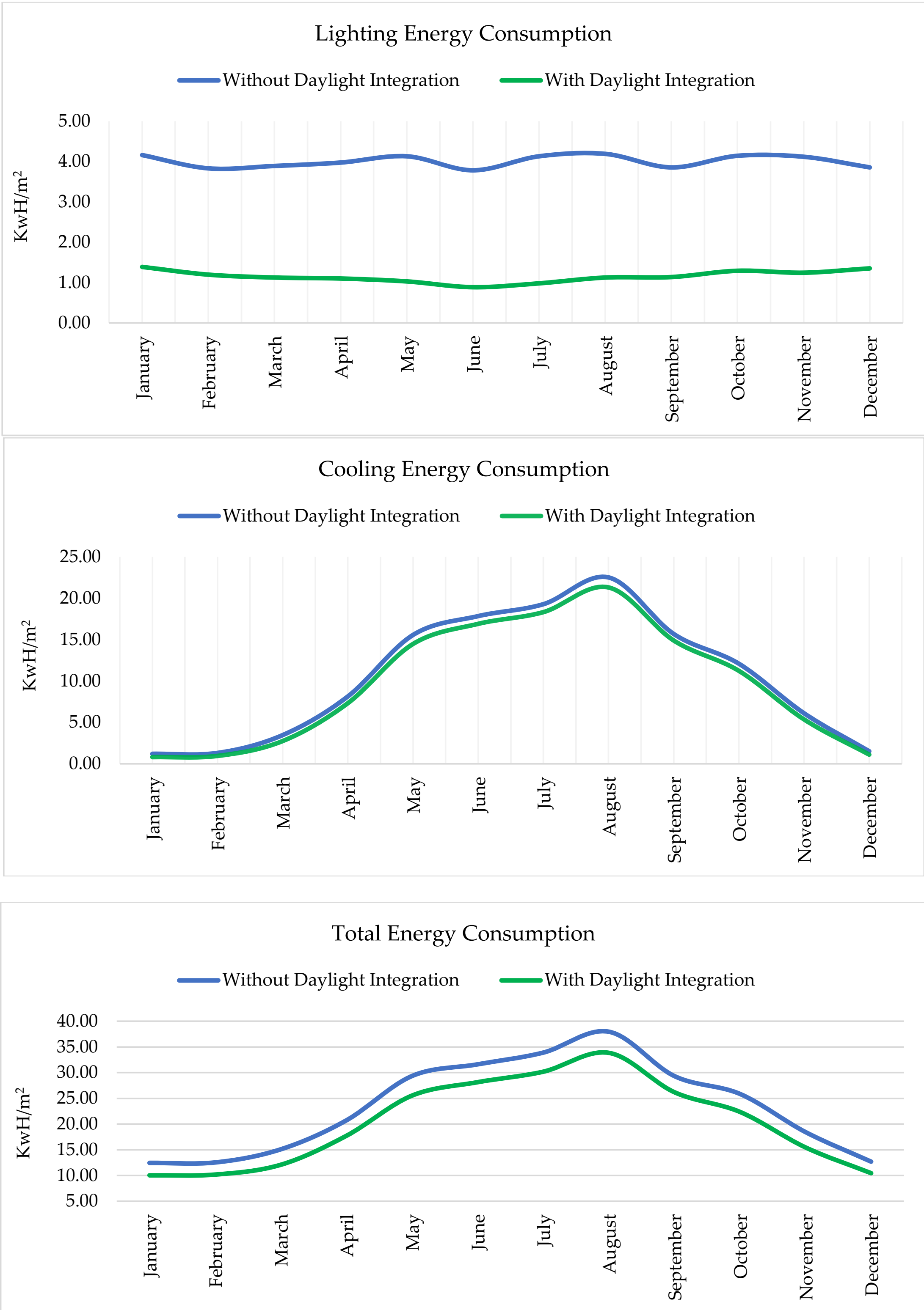

Figure 4. Total monthly electric energy consumption (lighting, cooling, and total) for modeled building with and without daylight integration.

4.3. Evaluation of Visual Comfort Performance with Low-E Glass Facades and Daylight Integration

The amount of natural daylight that may enter a space is influenced by orientation, window area, and glass type. Appropriate levels of daylight entering a space may lead to less use of electric lighting. The glare index was selected as an indicator in this study to assess the visual comfort status in each zone of the modeled building. The glare index is determined by the amount of light passing through the window. The office lighting level was adjusted to 500 Lux, and the comfort level for the glare index was set to 22, which is a recommended number (Jain, Karmann, & Wienold, 2022) [29]. The average glare index perceived by a user sitting near the perimeter wall was calculated by the DesignBuilder software. The first daylight sensor's location was used as a reference point to calculate the average glare index value. Figure 5 provides a comprehensive overview of the average glare index fluctuations resulting from variations in the building's orientation. The simulation outcomes highlight that the average glare index values for different orientations surpassed the recommended threshold. Notably, the north-oriented facades of the simulated building's base case model exhibited favorable ambient and indirect lighting conditions during the winter season, spanning from September to March. Although minor challenges associated with solar heat input were observed, the average glare index remained within an acceptable range, facilitating comfortable visual conditions for occupants within the building. These findings underscore the importance of considering orientation as a critical factor in achieving optimal lighting conditions while managing glare-related concerns.

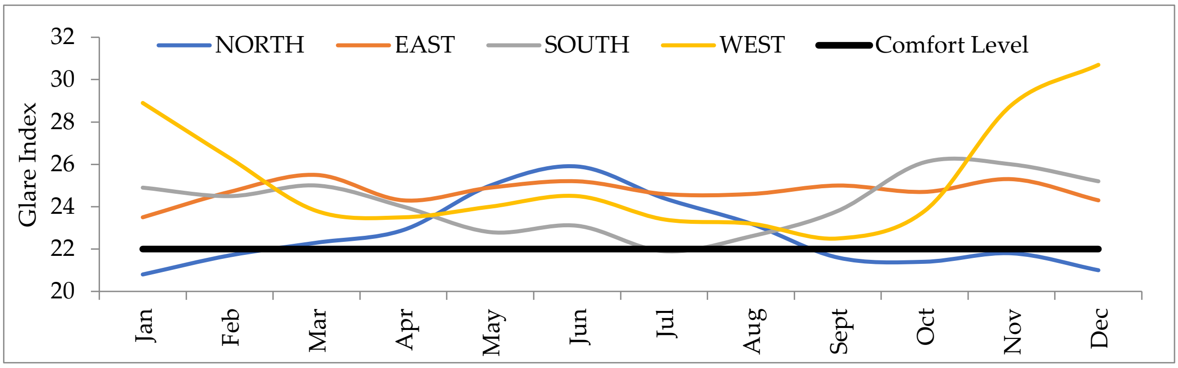

Figure 5. Calculated glare index value at various orientations of the office building model.

Controlling the glare index within the range of comfortable levels poses a considerable challenge for both east- and west-oriented facades, primarily due to their propensity for allowing significant daylight penetration and consequent increase in solar heat gain as a result of high sun angles. The direct sunlight that permeates through these orientations creates an imbalanced distribution of illumination levels between the interior and exterior of the building structure. The average calculated glare index value for the east and west orientations has been determined to be approximately 24.5. In contrast, the south-oriented facade exhibits notable shading capabilities during the summer months, effectively reducing undesired solar heat gain while simultaneously harnessing daylight to mitigate lighting energy consumption. The angle of the sun's trajectory is comparatively lower in the summer, which leads to a discernible increase in the average glare index. However, this orientation allows for the potential ingress of light and heat during the winter period when the angle of the sun is lower. Consequently, south-facing facades receive a greater influx of daylight during the winter season, as the sun remains positioned for a longer duration toward the south, resulting in an elevated glare index value. These findings underline the intricate balance between daylight admission, solar heat gain, and glare index management, necessitating thoughtful design considerations to optimize the visual environment while ensuring occupant comfort and energy efficiency throughout varying seasons and orientations.

4.4. Energy Performance of the Simulated Base Case Building Model with Electrochromic (EC) Glass Windows and Daylight Integration

4.4.1. Daylight Control Strategy

In order to evaluate the potential of EC smart glass windows for achieving energy savings and enhancing visual comfort within the office building model, a comprehensive retrofitting approach was implemented. Specifically, the existing double low-E glass was systematically replaced with EC smart glass across all orientations of the building. To facilitate the transition of the EC smart windows from an opaque to a transparent state, a carefully devised daylight control strategy was employed. Subsequent simulations were conducted to investigate the resulting energy savings and visual comfort in the different zones. The outcomes of these simulations are presented as follows:

Upon the installation of EC smart glass windows in all orientations of the office building, in contrast to the previous implementation of low-E glass with daylight integration, a notable additional reduction of 25% in lighting energy consumption was achieved. This significant reduction can be attributed to the high visible transmission property of EC glass, allowing a substantial amount of daylight to permeate when the windows are in their transparent state. As a result, the reliance on artificial lighting was minimized to the lowest feasible level, thereby yielding considerable energy savings. Moreover, the introduction of EC smart glass contributed to a further 9% reduction in cooling energy consumption within the modeled office building. This achievement can be attributed to the EC windows' ability to regulate solar heat gain and minimize unwanted thermal transfer, thus optimizing the cooling demands of the building.

Overall, the integration of EC smart glass windows resulted in a substantial reduction in the building's overall energy consumption, equivalent to an impressive 23%. This outcome underscores the significant potential of EC smart glass technology to simultaneously enhance energy efficiency, reduce lighting and cooling energy requirements, and improve the overall sustainability performance of office buildings. To assess the visual comfort conditions within each zone, the average glare index values for EC smart glass windows were carefully examined. This analysis aimed to determine whether the established visual comfort criteria had been successfully met. Figure 6 visually depicts the temporal variations in the maximum glare index values for both low-E glass and EC smart glass windows equipped with a daylight controller. During the evaluation, it was observed that the daylight transmittance through the EC glass windows was meticulously adjusted to align with the specified daylight illuminance set point, which was monitored by the initial daylighting sensor. However, despite these measures, it was determined that the glare index values exceeded the acceptable recommended threshold for all orientations. This outcome suggests that, although the implementation of EC smart glass windows effectively reduced the reliance on artificial lighting, it concurrently introduced an excess of brightness to the daytime illumination. Consequently, the heightened brightness levels resulted in discomfort among the building's occupants from a visual perspective.

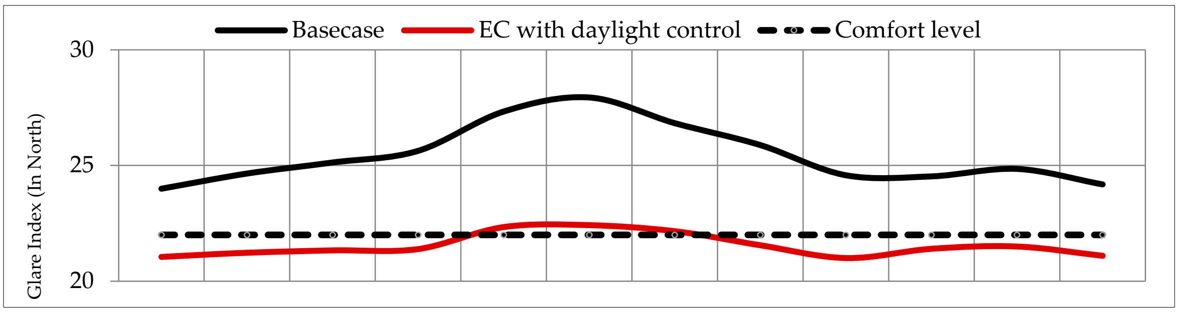

Figure 6. *Cont.*

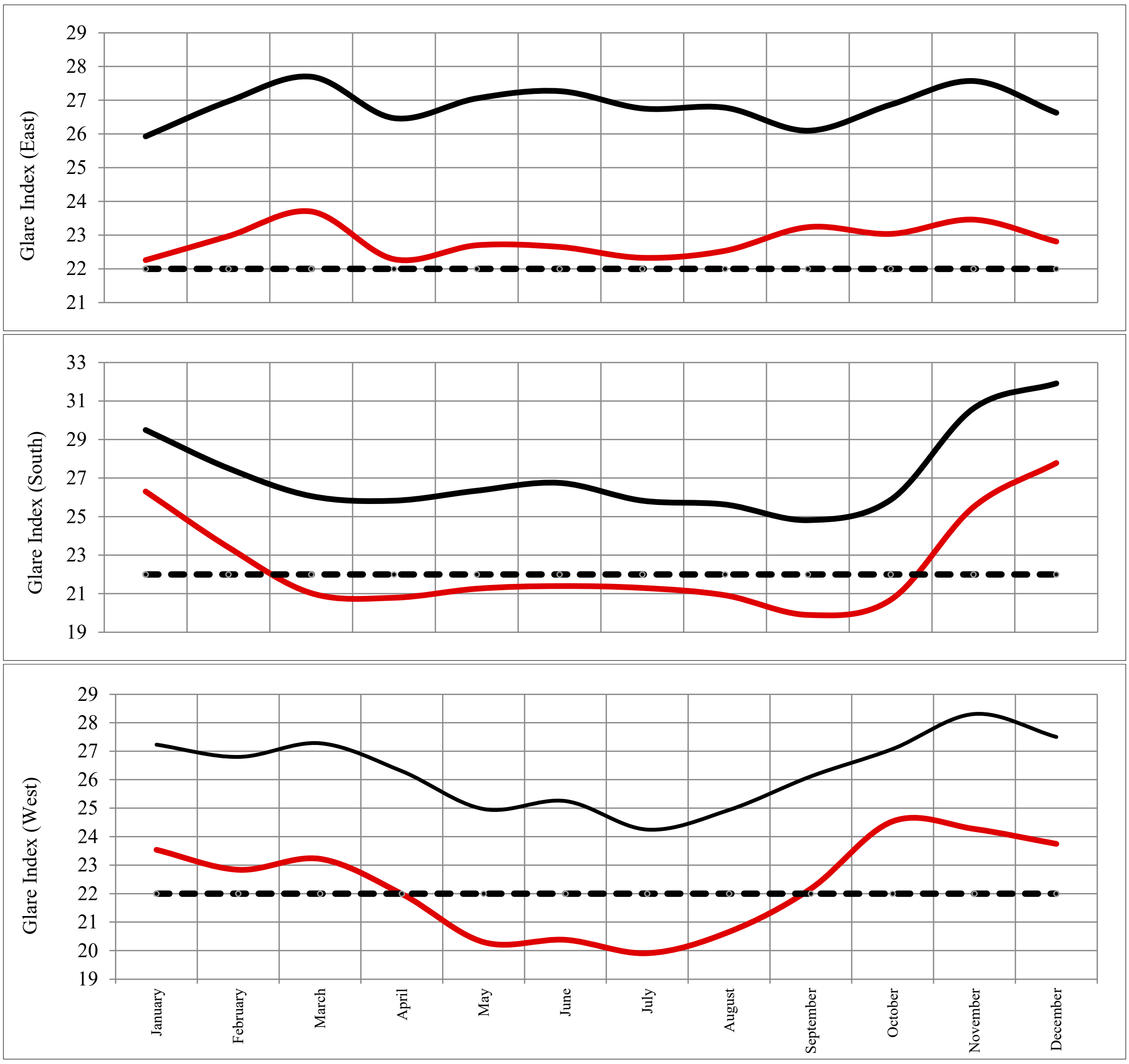

Figure 6. Variation in the maximum glare index value for the modeled office building with low-E and EC smart glass windows with daylight controllers at different orientations.

These findings underscore the intricate challenge of balancing the benefits of daylight integration with the imperative need to maintain optimal visual comfort. While EC smart glass windows contribute to reduced artificial lighting requirements, their potential to enhance visual comfort is limited due to the elevated brightness levels. Thus, a refined approach is warranted to achieve an optimal balance between daylight utilization and mitigating glare-related discomfort, ensuring the well-being and satisfaction of the building's occupants.

4.4.2. Glare Control Strategy

In order to mitigate glare issues and maintain a comfortable visual environment, the EC smart glass windows integrated with a glare control strategy were employed. This entailed dynamically modulating the window's transmission properties to effectively regulate the admission of daylight without compromising visual comfort. A series of simulations were conducted to assess the energy savings achieved and evaluate the visual comfort criteria within each zone of the office building. The simulation results demonstrated notable reductions in both lighting energy consumption and cooling energy consumption. Specifically, the implementation of the EC smart windows with the glare control strategy led to a significant 12% decrease in lighting energy consumption. This reduction can be attributed to the efficient control of daylight admittance, which minimized the need for artificial lighting, thus resulting in considerable energy savings. Moreover, the utilization of the EC smart glass windows contributed to a substantial 14% reduction in cooling energy consumption. By effectively managing solar heat gain and optimizing thermal transfer, the EC smart window system played a crucial role in reducing the cooling load and enhancing energy efficiency. Furthermore, the overall energy consumption of the building witnessed a substantial reduction of approximately 17% when compared to the combination of low-E glass with daylight integration. This remarkable decrease in energy consumption underscores the significant potential of the EC smart glass window system in delivering comprehensive energy savings and promoting sustainability within the office building. The outcomes of this investigation not only highlight the tangible energy-saving benefits but also underscore the importance of considering visual comfort criteria when implementing advanced green technology solutions. By effectively mitigating glare-related issues, the EC smart glass window system offers a promising approach to strike a balance between energy efficiency and occupant well-being in office environments. The observed variations in glare index values across the different orientations of the modeled office building are visually represented in Figure 7. To ensure a comfortable visual environment, an acceptable glare index set point value is established and integrated into the EC smart glass window sensor system. This set point serves as a crucial trigger for modulating the glass's state, transitioning it from a colored to a transparent state. By meticulously adjusting the transmittance properties of the EC smart glass to align with the desired glare index, as determined by the initial daylight sensor, the resulting glare index values for all orientations fall within the acceptable limits. This dynamic control mechanism allows for the admission of only a limited amount of daylight, as long as the glare index remains within the prescribed comfort range. Consequently, the implementation of the EC smart window system effectively reduces lighting energy consumption while concurrently ensuring optimal visual comfort for the building occupants across all zones. The employment of a glare control strategy specifically tailored for windows equipped with EC smart glass yields substantial energy savings in lighting, as well as a significant reduction in cooling energy demands. Additionally, the visual comfort criteria for all orientations within the office building are successfully met. The adoption of this strategy not only achieves remarkable energy efficiency but also enhances the occupants' overall satisfaction by mitigating glare-related discomfort.

Based on these compelling findings, the incorporation of a glare control strategy is strongly recommended for EC smart glass windows. This approach offers considerable potential to deliver substantial energy savings, enhance visual comfort, and promote sustainable practices within the office building environment. Therefore, it is crucial to carefully consider and implement the glare control strategy when deploying EC smart glass solutions, ensuring optimal performance and occupant well-being.

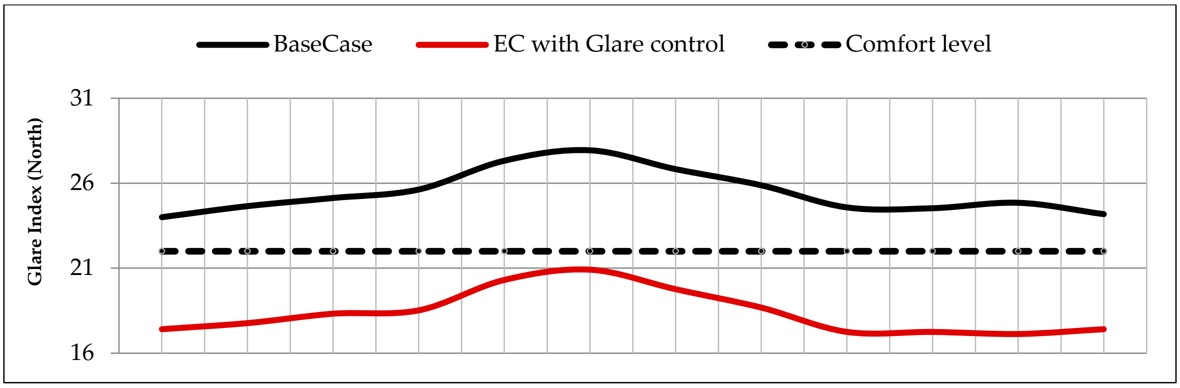

Figure 7. *Cont.*

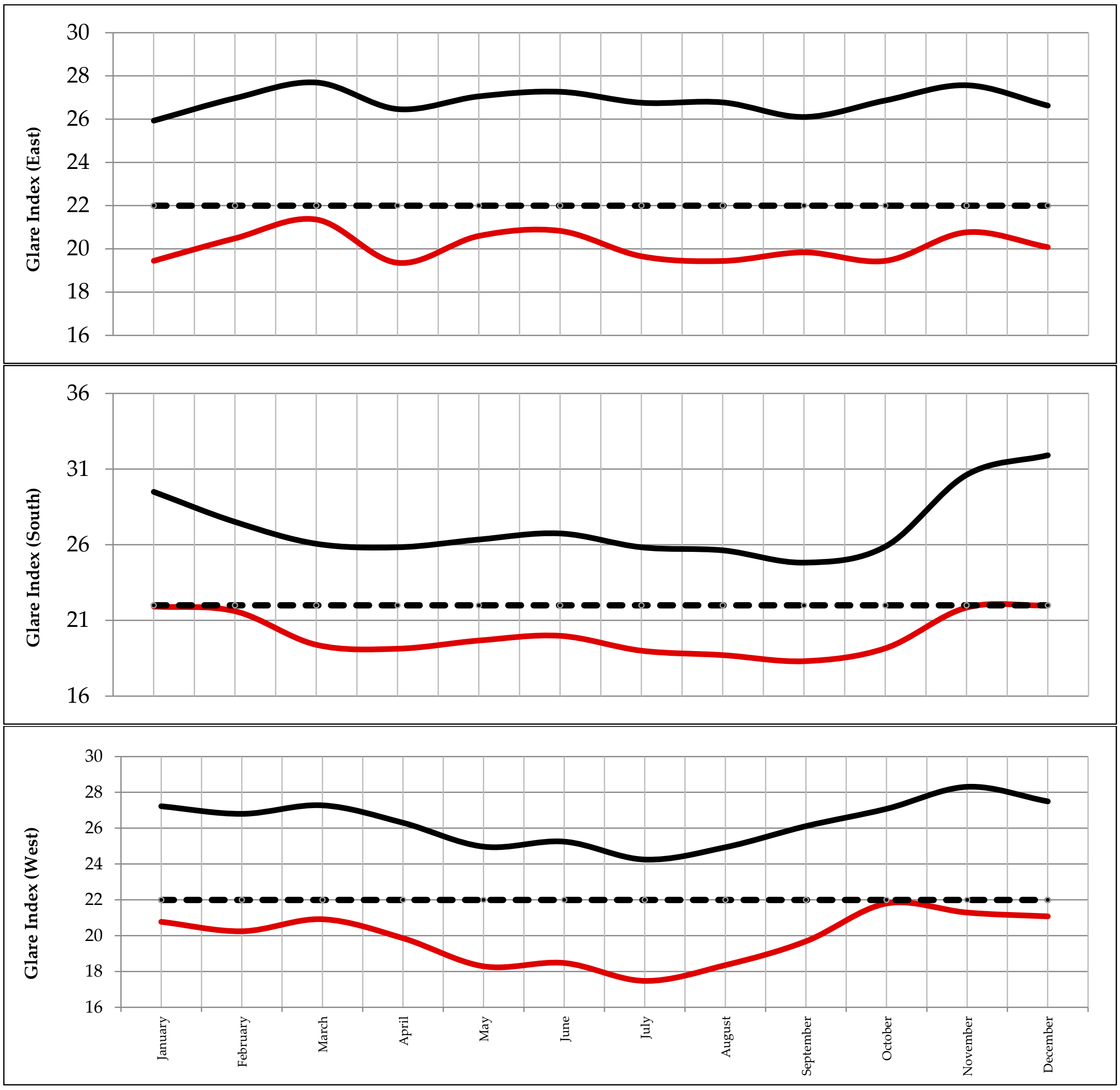

Figure 7. Variation in the maximum glare index value for the modeled office building with low-E and electrochromic smart glass windows with glare controller.

4.5. Payback Period Analysis for Using EC Smart Glasses Windows

In order to assess the cost-effectiveness of the proposed energy-saving measures, a comprehensive evaluation was conducted using the Simple Payback Period (SPP) approach. The SPP takes into meticulous account the upfront costs associated with the implementation of the energy-saving options, encompassing both the initial investment cost and the anticipated utility savings within the first year of operation. The SPP is determined by dividing the total cost of adopting the energy-saving measures by the projected annual energy savings achieved through their implementation. In this study, the electricity consumption attributed to the building's cooling system and artificial lighting was considered. Specifically, the initial cost of incorporating the EC smart glass technology was meticulously factored in. To obtain accurate pricing information, multiple suppliers of EC smart glass were diligently contacted and detailed pricing quotes were obtained. Based on the responses received, it was determined that the average cost of EC smart glass, inclusive of the necessary controllers, was approximately USD 240 per square meter. These cost considerations form an integral part of the analysis and provide valuable insights into the financial viability of implementing EC smart glass in the examined context. Based on the published literature and industrial experiments, the service life of EC smart glass is greater than 20 years (Vu, et al., 2022) [30]. The cost for electrical power was calculated using data published by the Saudi Electricity Company. The comprehensive research undertaken shed light on the prevailing tariff structure for office buildings, highlighting a standard pricing of USD 0.08 per kilowatt-hour (kWh). The SPP calculations for energy conservation opportunities and visual comfort are shown in Table 5. Based on this study's findings, employing EC smart glass windows with daylight control can save a significant amount of energy while still meeting the visual comfort criteria in some zones of the office building. Using a glare controller for an EC smart glass window, on the other hand, can save 17% of total building energy usage and satisfy the visual comfort in all the zones of the building with a payback period of approximately 6.37 years.

Table 5. Energy conservation opportunities with EC smart glass windows.

Energy Conservation Measure	Lighting Energy Savings (KWhr)	Cooling Energy Savings (KWhr)	Total Energy Savings (KWhr)	Visual Comfort	Area (m^2)	Cost of Installation (USD)	Cost of Energy Savings (USD)	Simple Payback Period (Years)
EC window with daylight control in all orientations	251,236	511,718	647,974	Not Achieved	2232	267,787	51,828	5.16
EC window with glare control in all orientations	199,196	585,397	524,839	Achieved	2232	267,787	41,979	6.37

EC smart glass window technology emerges as a highly promising and transformative advancement in the realm of energy-efficient windows. By harnessing its potential, significant strides can be made towards enhancing building energy performance and achieving sustainability objectives. The utilization of EC smart glass windows facilitates the concurrent reduction of both lighting and cooling energy consumption, while ensuring the preservation of optimal visual comfort standards throughout the building environment.

5. Discussion

The present research study delves into an in-depth exploration of the potential benefits that arise from the implementation of EC smart glass windows within an office building situated in a hot-humid climate, shown by the specific context of Dhahran, Saudi Arabia. The investigation discerns that by incorporating EC smart glass windows alongside daylighting control triggers, the overall energy consumption of the building can be effectively curtailed by 23%. Moreover, the study explains that when employing EC smart glass in conjunction with glare control triggers, the resultant energy savings amount to 17% for the entire building. However, it is crucial to highlight that while the utilization of EC smart glass windows with daylighting control triggers yields substantial energy savings, it falls short in attaining visual comfort standards across all zones of the building. In contrast, the implementation of EC smart glass with glare control triggers successfully ensures visual comfort in all zones. These findings underscore the potential of EC smart glass windows with glare control triggers to not only reduce energy consumption but also maintain an optimal level of visual comfort within office buildings situated in hot-humid climates.

The outcomes of this study align with previous research endeavors that have consistently demonstrated the advantageous implications of employing EC smart glass in buildings, manifesting in reduced energy consumption and improved visual comfort. The integration of EC smart glass windows stands as a formidable solution in the ongoing pursuit of enhancing energy efficiency within buildings. By harnessing the dynamic control capabilities of this innovative technology, building owners and occupants can smoothly navigate the dual challenges of lighting and cooling energy demand. The incorporation of EC smart glass empowers a judicious management of daylighting levels and solar heat gain, two pivotal factors profoundly influencing energy consumption. By efficiently capitalizing on the transmission of natural daylight, the implementation of EC smart glass windows propagates a substantial reduction in lighting energy usage by obviating the excessive reliance on artificial lighting sources. Additionally, the dynamic control mechanisms intrinsic to EC smart glass proficiently regulate the admission of solar heat, effectively alleviating the strain on cooling systems and culminating in notable energy savings in terms of cooling demands.

Significantly, the EC smart glass technology not only facilitates energy efficiency gains but also steadfastly upholds the imperative of maintaining visual comfort within the building environment. Through an intelligent balance between daylight admission and solar heat gain, the smart glass ensures that building occupants can relish a well-illuminated and thermally pleasant indoor atmosphere. This holistic integration of energy efficiency and visual comfort epitomizes a comprehensive approach to building design and operations, thereby engendering substantial benefits in terms of energy conservation and occupant satisfaction.

In summary, the study showcases the immense potential of employing EC smart glass windows within office buildings situated in hot-humid climates. The findings underscore the remarkable energy-saving capabilities of EC smart glass, particularly when coupled with glare control triggers. Furthermore, the study reinforces the pivotal role of visual comfort in shaping occupants' well-being and highlights the synergistic combination of energy efficiency and visual comfort as a cornerstone of effective building design. Ultimately, the integration of EC smart glass technology holds the promise of significantly advancing energy performance objectives while concurrently ensuring optimal visual comfort within the built environment.

6. Conclusions

In conclusion, this study presents compelling evidence demonstrating that the implementation of EC smart glass windows with a glare control trigger holds significant potential for both achieving energy savings and maintaining visual comfort within office buildings situated in hot-humid climates, such as Dhahran, Saudi Arabia. The findings presented in this research carry practical implications for architects and building owners, facilitating informed decision making regarding the adoption of EC smart glass windows in their respective buildings, while considering crucial factors such as energy efficiency, visual comfort, and the payback period. The analysis conducted in this study includes an assessment of the payback period associated with installing EC smart glass windows with glare control across all building orientations. Based on the calculated payback period, it is determined that the approximate payback period for the installation of EC smart glass with glare control in all orientations of the building is 6.37 years. This valuable economic information enables building owners and decision makers to evaluate the feasibility of investing in EC smart glass technology for their buildings, taking into account the anticipated return on investment.

It is important to acknowledge that further research endeavors may be necessary to optimize the control strategies for different building types and climates, thereby advancing the efficacy of EC smart glass technologies. Nonetheless, the present research study serves as a pivotal starting point, offering valuable insights and paving the way for future research and development in the realm of EC smart glass.

In summary, the findings of this study underscore the potential of EC smart glass windows with glare control triggers to contribute to energy conservation and enhance visual comfort in office buildings located in hot-humid climates. The outcomes of this research equip professionals in the field with pertinent information necessary for informed decision making, while also shedding light on the economic viability of implementing EC smart glass. Ultimately, this study serves as a catalyst for further advancements and progress in EC smart glass technologies, driving the pursuit of sustainable and energy-efficient building solutions.

Author Contributions: I.M.B. made significant contributions by collaborating with the second author to conduct the simulation study. This involved validating the office building model using the DesignBuilder software, analyzing the results, and evaluating the performance of EC smart glass windows in terms of energy savings and visual comfort for building occupants. M.A.F. played a pivotal role in conceptualizing the idea of implementing EC smart glass windows to achieve energy savings and enhance visual comfort in buildings. The combined efforts of both authors have greatly contributed to advancing the understanding of the potential benefits offered by electrochromic smart glass in improving building energy efficiency and ensuring occupant satisfaction in terms of visual comfort. All authors have read and agreed to the published version of the manuscript.

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