Simulation study for a switchable adaptive polymer dispersed liquid crystal smart window for two climate zones (Riyadh and London)

Abdulmohsin Hemaida*, Aritra Ghosh, Senthilarasu Sundaram, Tapas K. Mallick*

Environment and Sustainability Institute (ESI), University of Exeter, Penryn Campus

TR10 9FE, United Kingdom

*Corresponding author (s) ah803@exeter.ac.uk; T.K.Mallick@exeter.ac.uk

Highlights:

- The energy performance, annual daylight glare, and interior illuminance performance of PDLC window were evaluated by EnergyPlus in two climate zones.
- Building energy modelling evaluation was conducted by employing PDLC window using solar radiation and outdoor temperature as a control shading strategy.
- PDLC achieved the highest annual energy reduction by 12.8% and 4.9% in Riyadh and London, respectively.
- Percentage of annual glare and interior illuminance of PDLC were evaluated for three daylight zones for two weather conditions.
- In Riyadh, the PDLC window achieved the highest interior illuminance in the low daylight zone.
- In London the PDLC window achieved the highest interior illuminance in the intermediate daylight zone.

Abstract:

Polymer dispersed liquid crystal (PDLC) is an electrically switchable smart window, that can provide privacy and control solar radiation, resulting in a potential energy saving. The optical properties of the PDLC window can be altered from translucent to transparent when an alternating current power supply is applied. However, little attention has been paid to the PDLC smart window in terms of overall building energy performance. Therefore, this study aims to investigate the impact of the PDLC window on heating, cooling, and lighting loads and daylight performance, for an office building utilising energy building modelling and daylight analysis tool. The study is limited to two contrasting climate zones; an arid climate (Riyadh, Saudi Arabia) and a temperate climate (London, United Kingdom). The results showed that PDLC window was more effective in Riyadh (arid climate) with a cooling reduction of 12.8 % than London (temperate climate) with a heating reduction of 4.9 %. PDLC provided excellent interior illuminance in both cities.

Keywords: Glazing, Smart Window, PDLC Energy Performance, Green Building, Energy Saving, PDLC Simulation, Office Building Simulation

1. Introduction

Energy consumption has increased rapidly worldwide. This has caused damage to the environment, through for example, global warming and air pollution. Over the last few years, the Gulf Countries (GCC) had a steady growth in the construction industry which led to huge expansion in the size of cities. Consequently, the GCC countries are among the highest energy use and environmental greenhouse gas emission countries in the world. The building sector has the greatest contribution in this respect. Saudi Arabia is leading this expansion by 43% of the total construction project among the GCC countries. Saudi Arabia is implementing a compulsory Energy Efficiency Plan for the building sector with specific targets [1]. However, the private sector has major challenges to invest in energy efficiency measures due to the low energy prices [2]. In the last five years, the energy demand for both the residential and commercial buildings has increased at an annual growth rate of 10% [3]. The building sector in Saudi Arabia is responsible for 76% of the total energy consumption, as shown in Figure 1 that includes the residential, commercial, and governmental buildings [4]. In particular, the commercial and governmental buildings accounted for 27% of the generated electricity in Saudi Arabia.

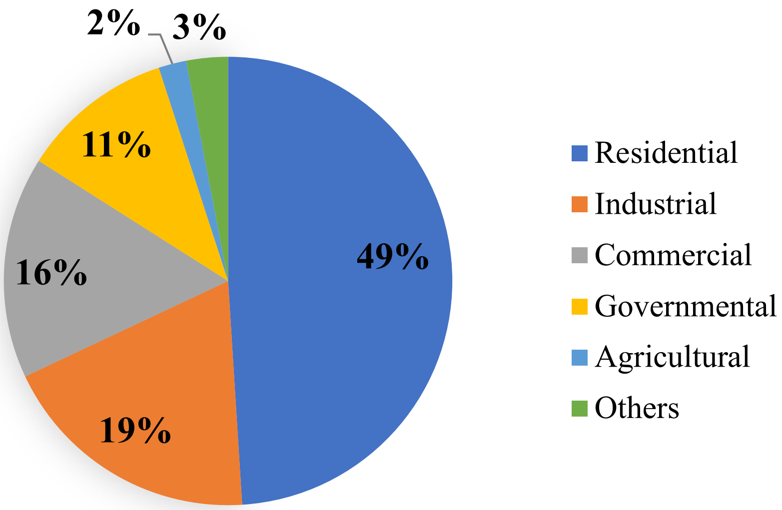
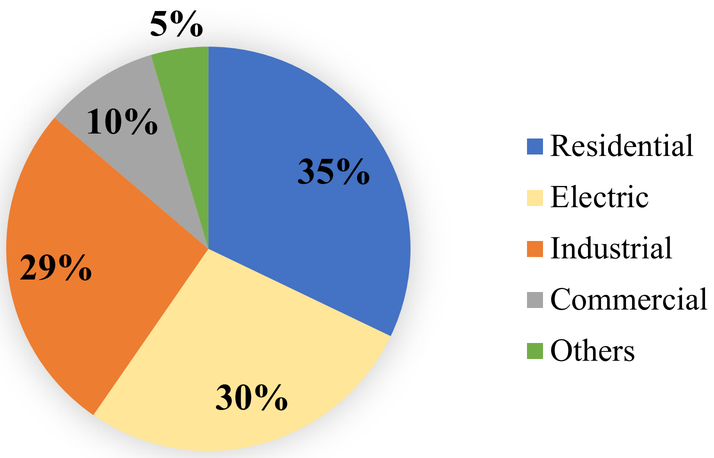


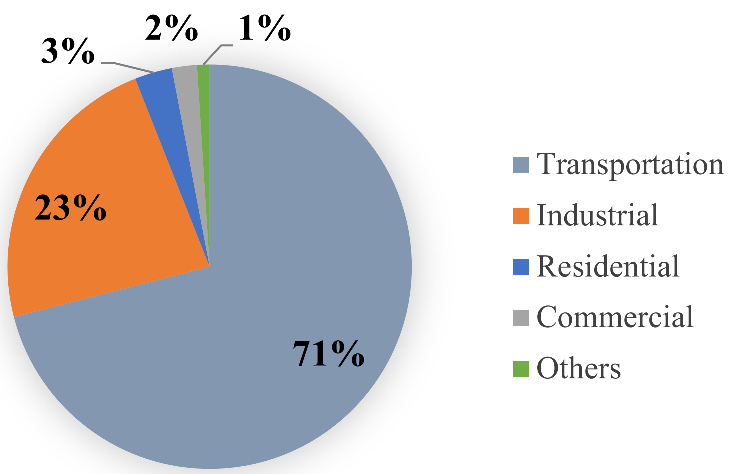
Figure 1. Energy consumption in Saudi Arabia in 2014 [4]**.**

In 2016, the United Kingdom was the second largest producer of petroleum and other liquids in Europe after Norway, and the third largest producer of natural gas in Europe. During the period of 2014 to 2016, the production of oil and natural gas production haver increased by an average of 9% and 4% per year, respectively [5]. Petroleum and natural gas are the most common fuel used for energy production in the UK; each account for 38% of the total energy consumption in 2016 [5]. Figure 2 reports the demand for natural gas and crude oil in the UK by sectors in 2016. Particularly, the commercial buildings consume 10% of the total natural gas production and 2% of the total petroleum production.

In the European Union (EU), the building sector utilises 40% of total energy consumption, which is responsible for 36% of CO_2 emissions [6]. The residential building sector consumes 25% of energy, leading to 16% greenhouse gas emissions [7]. Building activities such as cooling, heating, and artificial lighting contribute to significant concerns related to environmental issues and energy demand [8]. In this respect, it is essential to take decisive measures to reduce global energy demand and greenhouse gas emissions. Conventional building components, particularly windows, exhibit poor thermal insulation that significantly affects the energy performance of a building and the wellbeing of occupants.



a).



b).

Figure 2. The chart shows the energy demand in 2016 based on sectors in the United Kingdom. a) reports the natural gas consumption: b) reports the petroleum consumption [5]**.**

Different strategies can be utilised to improve building energy efficiency such as active or passive energy efficiency strategies. Active energy efficiency can be implemented by using improved heating, ventilating, air conditioning (HVAC) systems, and electrical lighting. Whereas, passive energy efficiency can be utilised by improvements to building envelope components. In recent years, considerable interest has been given to passive building energy efficiency. Fenestration plays a crucial role in building design, which adds aesthetic values, provides indoor thermal comfort, and natural daylight. In the last decade, there has been significant development in glazing technologies. Windows play an important role in the energy and environmental performance of buildings and significantly affects the levels of thermal and visual comfort for occupants. In general, occupants in a building receive natural daylight, air ventilation, and passive solar gain through windows. These vital functions make window selection very important, especially form energy usage and visual comfort. However, windows are responsible for approximately 60% of the total energy consumption in a building due to the high level of heat loss and heat gain [9]. *U*-value and solar heat gain coefficient (SHGC) are the major two factors that determine windows' energy performance. In order to abate heating and cooling loads, high SHFC and low *U*-value are required for cold climate and hot climate, respectively [10]. Thus, it is important that windows have appropriate SHGC and *U*-values to bring thermal comfort to occupants, as well as diminish energy demands. In addition, admitted solar radiation could have an adverse impact on the wellbeing of occupants, and on the degradation of materials inside a building [11].

Switchable windows can restrict both diffuse and direct solar radiation, whereas most passive shading devices and tinted glass can improve natural daylight during the early morning and afternoon hours when they are transparent [12]. Dynamic (smart/advanced/adaptable) switchable windows are a new class of window that can change optical and thermal properties according to occupants needs in response to an electric stimulus or changing environmental conditions [13]. Additionally, smart switchable windows and building applications would greatly reduce energy consumption and artificial lighting loads [14]. Currently, investigated electrically activated smart switchable windows include electrochromic (EC) [15]; suspended particles device (SPD) [16]; and liquid crystal (LC) [17]. While ECs are operated with direct current (DC) power supply; SPD and PDLC require alternating (AC) power supply [18].

EC window changes colour reversibly due to the oxidation and reduction reaction when DC power supply is applied [13]. This controls incoming solar radiation by modulating visible and near-infrared transmission, which can save up to 5-15 kWh/m^2 per year of the heating and cooling loads of commercial and residential buildings [19]. SHGC has been observed in EC windows at 0.49 in the clear state, and 0.09 in the full dark state with light transmission values ranging between 69% and 1%, respectively and a *U*-value of 3.8 W/m^2 K for both hot and cold climates [19]. EC devices switching time is reasonably slow; for instance, a 1.2 m × 0.8 m window requires approximately 12 minutes to switch from transparent to the opaque state [20]. EC devices can sustain a lifetime of 10^5 cycles with an operating temperature between -30 to 60°C [21]. At high operating temperature, EC power requirement is lower than its rated value [22], and after switching, EC does not need any power supply to maintain the coloured state [21]. Though EC window effectively reduces the building energy demand slow switching speed, low durability, and working under DC power supply make them a critical choice for large scale window application.

Alternatively, SPD [23] and PDLC both have fast switching, and work under AC power supply. SPDs comprises a polymer layer with light-absorbing and polarisable particles sandwiched between two transparent conductive thin films [24]. SPD's optical properties can be altered by applying the AC power supply to the active layer, which aligns in the particles parallel and yields a higher transmittance "on-state" [16]. The absence of a power supply results in randomly oriented particles and produces lower transmittance "off-state" [24]. SPDs can offer comfortable daylight with transmissions varying from 5% in the dark state to 55% in the transparent state [25]. In addition, SPDs can control the solar heat gain from 0.05 to 0.38 in the opaque and transparent states, respectively [26]. SPD's thermal characterisation has been investigated using a test cell in Dublin, which showed a *U*-value of 5.9 W/m^2 K for SPD single window, while the SPD double window was 2.98 W/m^2 K for both states [27].To improve the thermal insulation property further, the vaccum insulated SPD window was also characterised by using real environment experiment [28,29]. However, it is evident that SPD is not capable of controlling the NIR and not able to offer privacy in its opaque states [30].

Polymer Dispersed Liquid Crystal (PDLC) windows change transparency when an electrical power is introduced [31]. Switchable PDLC windows have an excellent potential for building applications. The PDLC windows have several advantages, for example it can be operated without polarisers, have high transparency transmission, large viewing angle, fast switching time, and the potential of controlling the transmission level [32]. Generally, PDLC films within a solid polymer matrix are composed of lower molecular weight micro-sized droplets of liquid crystal. These are situated between two separate transparent conducting electrodes. Due to the refractive index mismatch between droplets and the polymer matrix, PDLC scatters lights in the absence of power. Moreover, LC molecules are oriented to enable light to pass when the power supply is present as the refractive index between the polymer matrix and the droplets match. The droplets define PDLC scattering, whilst the radius of the droplets is smaller than the incident wavelength. This which enables light to pass through without any form of scattering. Indoor spectral characterisation of a PDLC window size of 0.2 × 0.15 m offered visible transmission of 71% for the transparent state and 27% for the translucent state SHGC varied from 0.53 to 0.39 for the transparent and translucent states, respectively [33]. This PDLC window was also able to maintain allowable daylight in temperate climate [34]. The relationship between the sky clearness index and the PDLC windows transmission by employing outdoor experiment was developed previously [35]. A PDLC window has been investigated using a smart room equipped with sensors and a computer system, which can control the PDLC transparency based on sun exposure and occupant motion inside the smart room [36]. The computer can detect the sunlight and the occupant motion then adjust the PDLC transparency accordingly. The performance of the PDLC was compared against a typical room with standard system. The investigation results showed that the PDLC window was able to reduce the energy consumption by 38% in comparison to the standard system and provide privacy in the room. PDLC films have shown 98% UV blocking performance, and modulating the NIR in the range between 12 and 38% and 3 million cycles durability at applied voltage of 100 VAC, 60 Hz, and a switching interval of 1 sec [37]. PDLC window can change its transmission according to the users needs by varying the voltage [38]. Although the PDLC window suffers from haze, manufacturers are investigating to produce haze-free PDLC [39]. In recent work, PDLC also lowered the light transmission, which was shown to be beneficial for reduction of elevated solar cell temperature [40]. However, the presence of haze in the PDLC window can make it a potential candidate for solar energy control and aesthetic and privacy applications, which are essential criteria for building. [41]. The privacy factor in PDLC glazing could be desirable in the workplace, for example in Saudi Arabia where gender separation applies, however, in the UK gender separation is not an issue. The PDLC window can be a potential building envelop that offers an ideal solution for the Saudi Arabian society to fulfil the need for privacy and provide energy efficiency for buildings. Moreover, The Gulf region faces huge chanllenges in terms of energy demand and environmental issues due to factors such as growing population, economy growth, and modernization. The average energy consumption in the GCC countries is over seven times higher than the global average consumption. In terms of environmental, the six GCC countries are the amongst the 15 highest countries in the world for their per capital Co_2 emissions. The GCC countries aim to adopt common objectives in terms of economic, legislation, and culture [1]. In this perspective, switchable PDLC window can have a good potential to mitigate the energy demand in the Gulf region. Saudi Arabia is undertaking a large-scale development in terms of renewable energy and energy efficiency for new and existing buildings. A retrofit programme has been suggested by the King Abdullah Petroleum Studies and Research Center (KAPSARC), which will significantly impact the electricity reduction by 10,000 GWh/ year and carbon dioxide emission by 7.9

million tonne/ year [42]. In the retrofit programme, different types of energy efficiency measures were proposed for existing building including window replacement, cooling system replacement, and installation of daylight system control.

Although the PDLC has considerable positive attributes for low energy building applications, studies related to building energy consumption using the PDLC smart window is limited in the literature. Only one study is available in the literature, which investigated the performance of the PDLC smart window in Korean climate conditions. The current study, for the first time, investigates the impact of the PDLC smart window for an office building in two different climatic zones (Riyadh and London) by employing building energy simulation approach. Currently, new design of office buildings trend to have large glazed areas, which allow large amount of incident solar radiation. Incident solar radiation and ambient temperature can potentially lead to thermal discomfort, due to glare and overheating risks, respectively. The shading control strategy for adaptive façade on energy consumption and indoor comfort should correspond to two dynamic changes instantly outdoor environmental conditions, and user comfort needs [43]. In the literature, adaptive glazing has been investigated by employing various control variables including outdoor temperature [41,44] and solar radiation [45,46]. In addition, a number of studies utilised weather file information including ambient temperature and solar radiation to control the shading strategy [46,47]. In this study, outdoor temperature and solar radiation, are two influential parameters that control the building energy demand, were chosen as the shading control variables. The performance of the PDLC window was analysed for an office building in London and Riyadh, with respect to its correlation to control transmittance, and the effects on energy loads and daylight performance. The results of this research can constitute valuable information for architects and engineers to predict the performance of PDLC switchable windows for green buildings.

2. Methodology

This study attempts to evaluate the effect of the PDLC switchable window for an office building to evaluate the cooling, heating, and lighting energy for two climate zones; and to compare the results against a double pane reference window. The building model was developed utilising Rhinoceros© modelling tool, integrated with a graphical algorithm editor Grasshopper© [48]. The software has excellent capabilities that enable modelling for energy and daylight simulation. Several scripts have been developed and integrated with Grasshopper© tool to perform building energy simulation such as Ladybug and Honeybee [49]. Grasshopper© can provide components such as EnergyPlus/ OpenStudio and Radiance/ Daysim to perform thermal and daylight analysis. This software was utilised as the main tool to investigate the PDLC switchable glazing to evaluate the cooling, heating, and lighting loads and daylight performance for an office building.

Windows are an important building component that can help to achieve energy balance and provide visual comfort. To evaluate windows performance for buildings, the required windows parameters are *U*- value and SHGC, and daylight. In the summer months heat passes through windows into the building and in the winter months heat escapes. The new technology of windows for example, multilayer glazing, low emissivity (low-e) glazing, and vacuum glazing could provide energy balance as they have competitive *U*-value. However, these window technologies do not have variable *U*-value and SHGC. Double glazing windows are commonly used in existing buildings due to low cost but they can not control daylight and glare. However, switchable windows can have variable *U*-value and SHGC and have the potential to offer visual comfort. Therefore, in the current research the reference window was chosen to represent the standard double glazing window that commonly used in the old existing buildings. The PDLC window used in this study was investigated by the authors in a previous study to determine the thermal and optical properties [50]. The reference window was obtained from the EnergyPlus database library, which has thermal properties close to standard double glazing window [51]. EnergyPlus 8.9 component was utilised to assess the energy saving for an office building for arid climate zone; Riyadh, Saudi Arabia, and temperate oceanic climate zone; London, United Kingdom. EnergyPlus was developed by the Department of Energy of the US government and has been made available for the public to perform annual building energy simulation. The software combines the best feature of BLAST and DOE-2 programs [52] and utilises the heat balance energy method, recommended by ASHRAE as the proper method for building energy modelling [53]. The capability of EnergyPlus has been extensively tested and validated for performing building energy analysis [54]. EnergyPlus is an excellent tool that allows users to investigate the switchable window and provides comprehensive data for annual analysis of heating, cooling, and lighting loads on an hourly basis [55,56]. The construction of the model used in this study is characterised by building geometry, envelop properties, mechanical system properties, lighting system properties, occupancy schedule, and HVAC system setpoint. More details of the model building and envelop properties are provided in section 2.3.

In this study, both the PDLC switchable window and reference window were defined in the simulation algorithm by three parameters: solar heat gain coefficient (SHGC), thermal transmittance (*U*-value), and visible transmittance (Tvis). Data analysis was carried out to evaluate the heating, cooling, and lighting loads for the office building on an annual basis. Two control shading strategies were utilised to control the PDLC window in two different climate zones. First, five solar radiation variables were used to control the PDLC window in Riyadh and London. Second, three variables of outdoor temperature were chosen to control the PDLC window in the same cities.

2.1. Daylight performance

OpenStudio 2.9 component was utilised to evaluate the interior illuminance performance and daylight glare index (DGI) of the investigated PDLC window. OpenStudio is an open source tool that allows advanced thermal and daylight analysis for building modelling. It is a strong tool used to perform energy performance analysis for both residential and commercial buildings [57]. To investigate the potential of the PDLC switchable window, which can improve indoor visual comfort, an analysis of glare metrics should be considered.

Discomfort glare caused by natural daylight and artificial lighting has been studied in the past and several metrics methodologies have been proposed to measure glare phenomena. The Visual Comfort Probability (VCP) method [58], the CIE Glare Index (CGI) [59], and the Unified Glare Rating (UGR) system [60] are methods that applicable for evaluating glare coming from artificial lights or uniform light source. In addition, none of these methods are suitable for predicting discomfort glare coming from sunlight [61]. British Glare Index (BRS or BGI) system [62] is appropriate for small glare sources that has solid angles inferior to 0.027 sr [63], without mentioning the monitoring procedure of the required parameters [64]. Most of these methods are not sufficient for evaluating user comfort as they react only to the horizontal illuminance. Daylight glare probability (DGP) is a method that evaluates glare in a simplified way in correlation between the vertical illuminance to the levels of glare [65]. Additional elements have to be considered to evaluate glare discomfort from windows such as the magnitude of discomfort glare which substantially depends on the brightness of the sky portion visible from the window. Glare originated from daylight at mild degrees seems to exhibit greater tolerance effects compared to the glare originated form artificial lighting source, however, it may not be noticeable at higher glare level [61]. Glare sensation is affected by non-uniform luminance distribution from windows [66].

In this study, Grasshopper© was used to evaluate glare discomfort for an office building. The software allows to evaluate glare discomfort using Daylight Glare Index (DGI) or Daylight Glare Probability (DGP) methods. The objective of the current study is to evaluate glare discomfort on an annual basis for every hour of the operation schedule. DGP is an image-based metric and would not be appropriate for annual based analysis. Therefore, DGI was more suitable to evaluate the visual discomfort for this study.

The OpenStudio component was used to evaluate the DGI and interior illuminance for the south orientation of the first floor, and natural daylight only was considered for the analysis. The evaluation of DGI was based on the percentage of time in which the DGI value was 22 or below for the total annual operation schedule hours. The maximum recommended value for office buildings is 22 which defines the borderline between comfortable and uncomfortable glare level (see Table 1) [67]. The discomfort glare at a reference point results from luminance difference between a window and an interior surface surrounding the window.

Table 1. Levels of discomfort glare indexes.

DGI level	DGI index
Just perceptible	16
Perceptible	18
Just acceptable	20
Acceptable	22
Just uncomfortable	24
Uncomfortable	26
Just intolerable	28

The interior illuminance was calculated as percentage of time for the total annual schedule hours and the illuminance setpoint was set to 300 lx. The analysis of the interior illuminance considered natural daylight only. Artificial lighting was controlled to dim when there was enough natural daylight. All sensors were facing the window view and the data of DGI and interior illuminance were calculated as a percentage of the total annual time. The DGI was calculated by:

$$G = \frac{L_{\omega}^{1.6}\Omega^{0.8}}{L_b + 0.07\omega^{0.5}L_{\omega}}$$

Where

G = discomfort glare constant

L_{ω} =average luminance of the window as seen from the reference point

Ω = solid angle subtended by window, modified to take into account the direction of occupant view.

L_b =luminance of window into N_x by N_y rectangular elements, as is done for calculating the direct component of interior illuminance.

To accomplish the balance between adequate daylighting level and energy usage, artificial lighting should be used when the amount of daylight in the room is insufficient. It was suggested by Velds and Christoffersen to divide a room into three daylighting zones, considering on the distance of a daylight zone from the window.[68]. The room was divided into three daylight zones (high daylight zone, intermediate daylight zone, and low daylight zone) to establish an appropriate evaluation of the discomfort glare and the interior illuminance. The effective window height was calculated by eq 1 The daylighting zones were divided into three zones, as follow:

1. High daylight zone (where artificial lighting is not usually required) starts from the window and has a depth of 2 x EWH.

2. Intermediate daylight zone starts from the end of the high daylight zone to a depth of 1.5 x EWH.
3. Low daylight zone (where the artificial light is required) starts from the border of the intermediate daylight zone to the end of the room.

$$EWH = \frac{ab\tau}{c} \quad (1)$$

Where EWH is effective window height (m); abτ effective window area (m^2); ab the actual window area above 0.9 m from the façade (m^2); a the width of the window (m); τ the transmission of the window plane; c the width of the façade. Figure 3 shows the reference points of the daylight glare index for all three daylight zones.

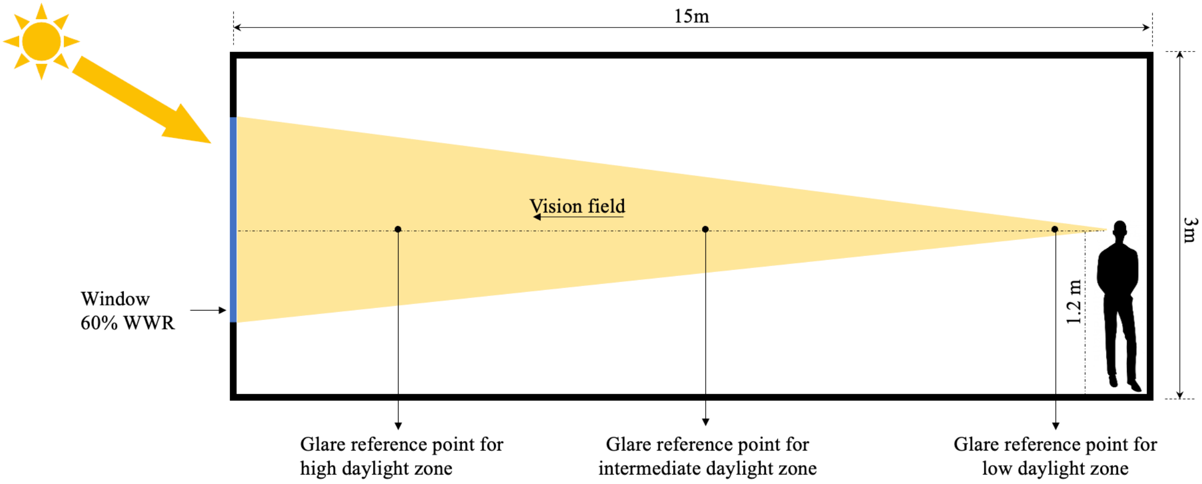


Figure 3. Illustration of DGI reference points and daylight zones.

2.2. Dynamic switchable window properties

Switchable PDLC film was purchased from HOHO industry and employed in this research to perform building energy analysis. The film has a dimension of 0.15 m × 0.14 m and thickness of 20 µm and requires 20 V AC to switch from translucent state to transparent state. To fabricate the window, the film was sandwiched between two 4 mm thick low iron glasses. Figure. 4 illustrate the schematic operation behaviour of the PDLC window in both the translucent and transparent states.

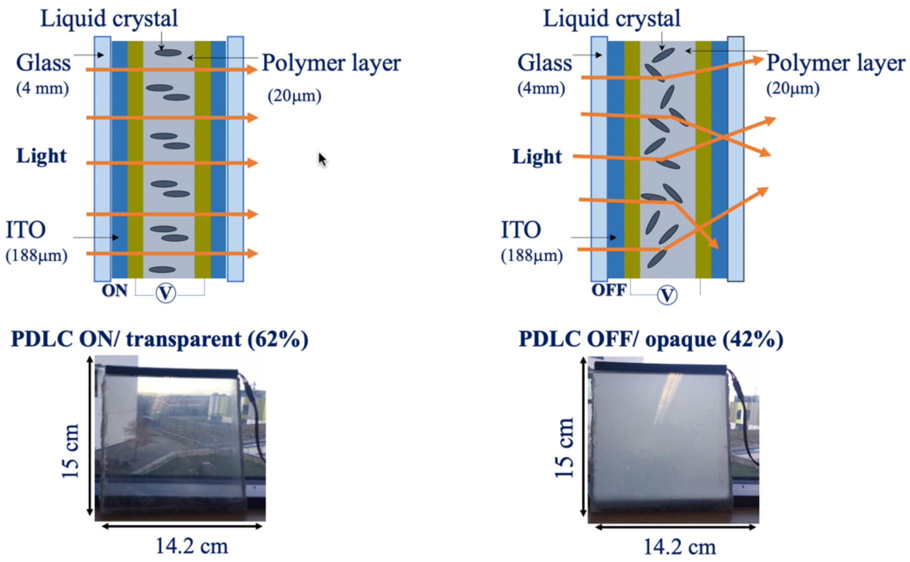


Figure. 4. PDLC window ON (transparent) and OFF (translucent) state.

Optical properties of this smart glazing were evaluated using a spectroscopy experiment and details of solar transmission and reflection data was obtained. The thermal performance of PDLC glazing was characterised by indoor test cell using a AAA type indoor solar simulator to determine the solar heat gain coefficient (SHGC) and thermal transmittance (*U*-value). Table 2. reports the optical and thermal properties of the investigated PDLC glazing.

Table 2. The optical and thermal properties of PDLC window for the transparent and translucent states.

Properties		**PDLC OFF (translucent)**	**PDLC ON (transparent)**	**Reference window**
Solar transmittance total (300–2500)	total	42%	62%	-
Solar reflectance total (300–2500)	total	18%	17%	-
Visible transmittance total (380–780)	total	44%	79%	81%
Visible Reflectance (380-780)	total	24%	18%	-
SHGC		0.63	0.68	0.76
***U*-value**		2.44 W/m^2 K	2.79 W/m^2 K	3.1 W/m^2 K

2.3. Building model

In order to evaluate the impact of PDLC glazing in enhancing the energy performance of an office building the heating, cooling, and lighting loads and daylight performance were investigated by EnergyPlus 8.9. The developed prototype building is a hypothetical model with ideal constructions that meet the minimum requirements of ASHRAE standards 90.1 [69]. Figure 5 shows the building model, which comprises four perimeter zones and two core zones. The model envelope properties were constructed as required by the American Society of Heating, Refrigerating and Air-conditioning Engineers ASHRAE standards (see Table 3). The selected model is a two-story office building with a total conditioned area of 4391.29 m^2, a floor height of 3 m, and a 60% window to wall ratio. An ideal air load system was adopted from the EnergyPlus library and used as an HVAC system to eliminate mechanical related problems. The heating and cooling setpoint during occupied hours were set to 20 °C and 26 °C. The internal load contributed by equipment was 7.6 W/m^2, artificial light was 11.8 W/m^2, and people were 0.0565 person/ m^2 as recommended by ASHRAE standards [70]. The operation schedule was selected adopting a typical office building type starting from 8:00-16:00 hrs from Monday to Friday.

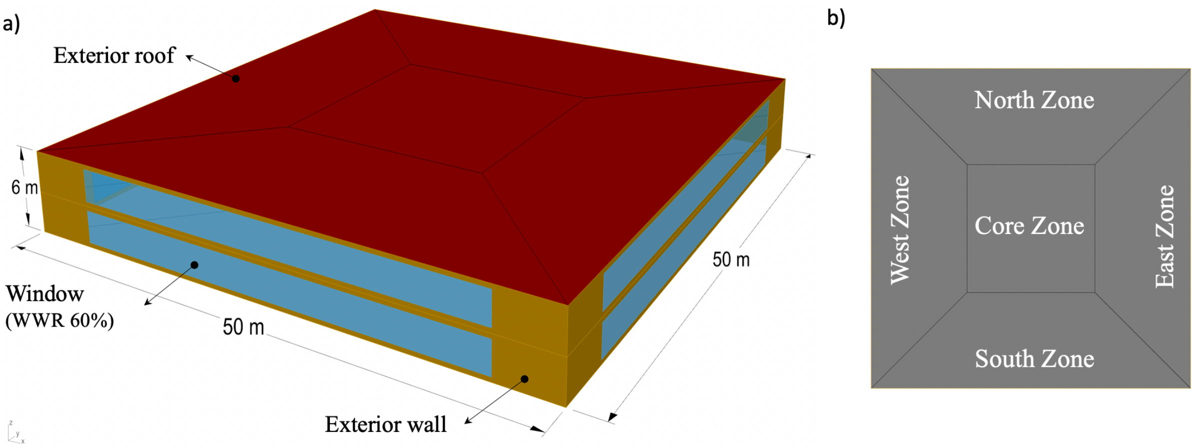


Figure 5. a) The picture presents a two-story office building model with 60% window to wall ratio. b) shows the perimeter zones.

Table 3. The envelope properties of the model building.

Construction	United Kingdom	Saudi Arabia
	U-Factor [W/m^2-K]	*U*-Factor [W/m^2-K]
Exterior Wall	0.591	2.377
Exterior Roof	0.273	0.358
Exterior Floor	2.945	2.945

2.4. PDLC shading control strategy

The PDLC switchable window can be operated by electrical power to switch to ON/OFF state; its optical and thermal properties can be controlled by users. The shading control of the PDLC can be categorised by manual control according to user needs and automatic control by the external environmental conditions. The automatic control includes variables such as outdoor temperature, indoor temperature, solar radiation, and external illuminance. From the user perspective, the objective of the PDLC switchable window is to control its properties in order to obtain indoor comfort. The objective of this study is to assess the PDLC performance at the highest and lowest temperatures for the selected climates. The highest and lowest temperature vary significantly and to achieve better evaluation another temperature 20 ◦C was chosen to evaluate the PDLC performance at the same outdoor temperature in two contrasting climates. Therefore, this study limited the control strategy to external environmental conditions in relation to outdoor temperature and solar radiation in order to achieve the optimum control variables.

In this study, the PDLC window was controlled by the solar radiation and the outdoor temperature. Each control strategy contained several variables and each variable was simulated independently in both strategies to avoid contradictions in the algorithm logic. Figure 6 illustrates the switching logic of the PDLC window where only one variable is selected to perform the simulation. The PDLC was controlled by various solar radiation levels upon vertical surfaces of the window. In addition, several outdoor temperature variables including the minimum and maximum temperatures were used to control the PDLC window. The PDLC shading control variables utilised in this study were set as follows:

1. The PDLC window was controlled by changing the solar radiation levels on the vertical window surface. When the solar radiation on the window surface exceeded the setpoint of 100 W/m^2, 250 W/m^2, 500 W/m^2, 750 W/m^2, and 1000 W/m^2, the PDLC changed to translucent; otherwise, it became clear.
2. The PDLC window was controlled by changing the outdoor temperature. When the outdoor temperature setpoint exceeded the minimum (Riyadh 4 ºC) and (London 5.9 ºC), maximum temperature (Riyadh 46 ºC) and (London 31.3 ºC), and 20 ºC, the state of PDLC window changed to translucent, and if not, it remained clear.

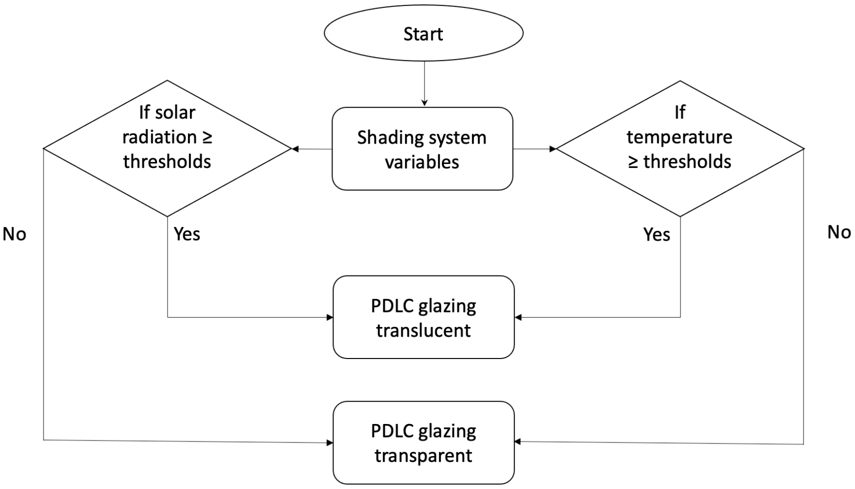


Figure 6. A workflow chart that illustrates the shading control strategy. The system simulates each variable independently for each control strategy.

2.5. Weather Data and Climate Zone

The weather data files used in this study were obtained from the EnergyPlus website [71]. Both cities (Riyadh and London) used in this study were a representative of the climate characteristics for each zone. The climate zones for Riyadh and London were classified according to Köppen-Geiger climate system [72]. Riyadh is located in Saudi Arabia (24°38N 46°43 E) and has an arid climate. The weather in Riyadh is hot and dry during the summer season where the highest temperature reaches 46 ºC, while in the winter the temperature drops to 4 ºC. London is located in the United Kingdom (51°30 N 0°39 W) and has a temperate oceanic climate. In London, the annual highest temperature in summer is 31.3 ºC, while in the winter is -5.9 ºC. Table 4 reports the weather temperature in both cities. Figure 7 presents the mean air temperature in the two climates regions throughout the year.

It is evident that Riyadh has the highest mean temperature of the two cities. Consequently, due to the two climate zones characteristics, an analysis was undertaken of the PDLC window energy and daylight performance based on the control conditions (mentioned in Section 2.4).

Table 4. Results of the weather data analysis for Riyadh and London climate zones.

		Riyadh	**London**
Air Temperature (ºC)	Max	46	31.3
	Min	4	-5.9
	Average	26.2	10.2

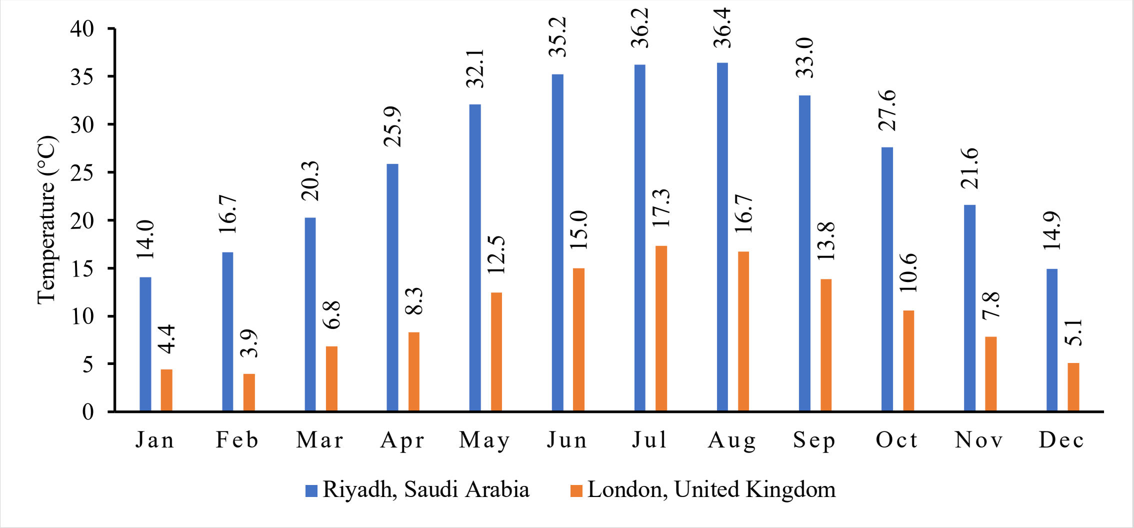
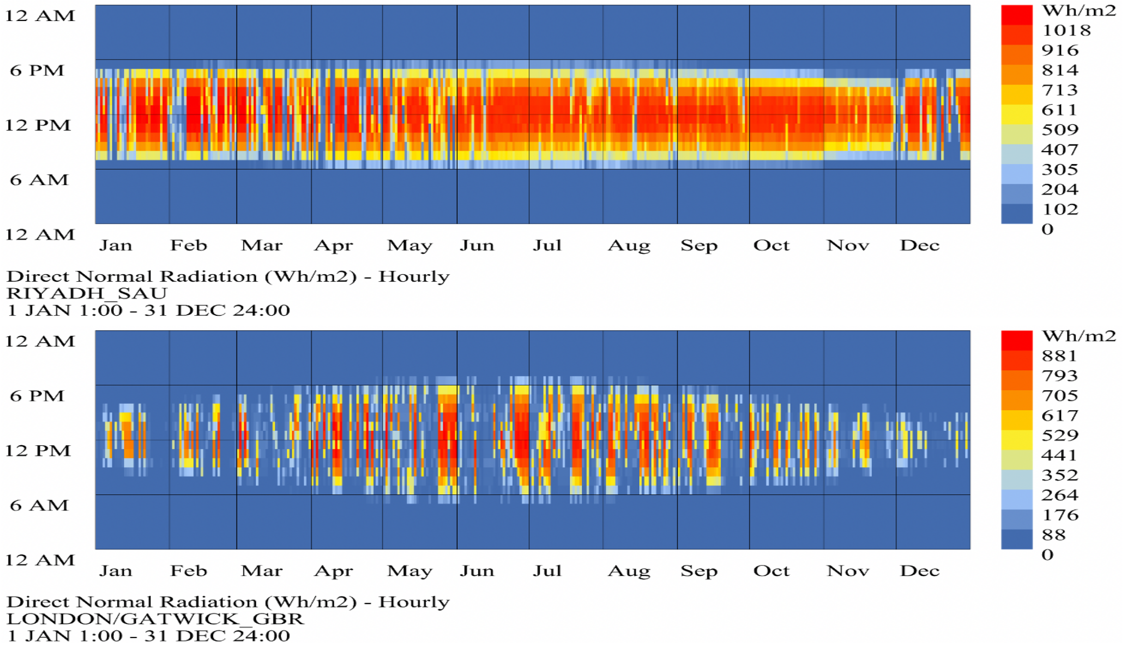


Figure 7. Results of mean air temperature for Riyadh and London climate zone.

Figure 8a reports the hourly direct solar radiation in Riyadh, Saudi Arabia and London, United Kingdom. The annual direct solar radiation in Riyadh varies from a minimum of 102 W/m^2 to a maximum of 1018 W/m^2. In general, Riyadh receives high amount of direct solar radiation throughout the year. However, in the summer months the mount of direct solar radiation is higher than the rest of the year. In London, the amount of direct solar radiation ranges from 88 to 881 W/m^2 from January to December. Figure 8b shows a comparison of the monthly average of the amount of direct solar radiation between Riyadh and London. The graph shows a clear difference in the monthly average amount of direct solar radiation between Riyadh and London. The highest average value for direct solar radiation in Riyadh can be seen in July (317 W/m^2), whilst in London it can be seen in May (143 W/m^2). The lowest average amount of direct solar radiation can be seen in December for Riyadh (119 W/m^2) and for London (22 W/m^2).



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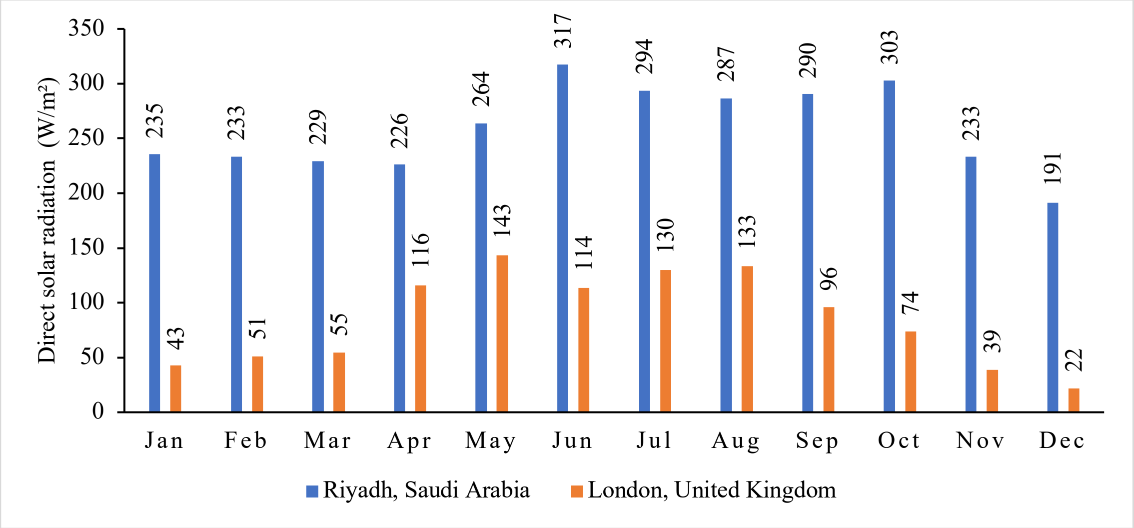
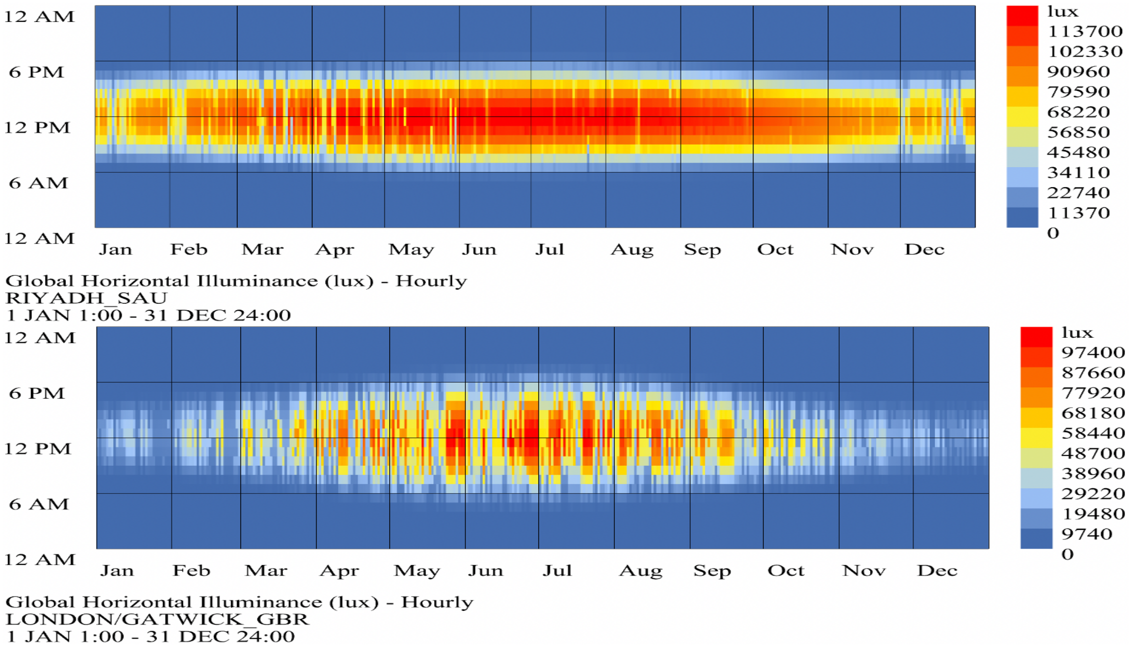


b).

Figure 8. a) The graph reports the hourly direct solar radiation in Riyadh and London. b) shows the monthly average of direct solar radiation.

Figure 9a presents the hourly global horizontal illuminance in Riyadh, Saudi Arabia and London, United Kingdom. In Riyadh, the amount of global horizontal illuminance is higher in the summer months than the winter months. The amount of global horizontal illuminance in Riyadh varies between 11,370 to 113,700 lux from January to December. In London, the global horizontal illuminance can reach to a maximum of 97,4000 lux and a minimum of 9,740 lux. Figure 9b presents a comparative data of the monthly average of global horizontal illuminance between Riyadh and London. In Riyadh, the highest monthly average value of global horizontal illuminance is in June (35,646 lux), whilst in London the highest average value is in July (23,149 lux). Both cities have the lowest monthly average of global horizontal illuminance in December of 16,197 lux and 2,496 lux for Riyadh and London, respectively.



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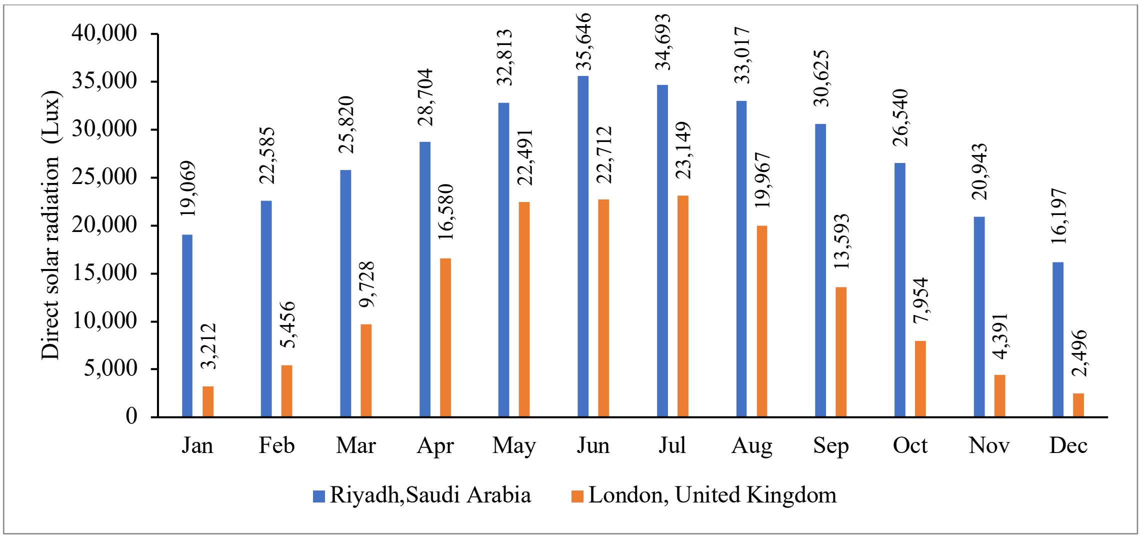

b).

Figure 9a. The graph presents the annual global horizontal illuminance in Riyadh and London. b) presents the monthly average values of global horizontal illuminance.

3. Results and discussion

Comprehensive analysis of the thermal and daylight performance for the switchable PDLC window for an office building are discussed in the following paragraphs. The analysis of the results was carried out using energy modelling and daylight analysis software. In the current study, two control strategies were utilised with respect to solar radiation and outdoor temperature for two different climate zones, Riyadh, Saudi Arabia (arid climate) and London, United Kingdom (temperate climate). Analysis showed that there was no energy saving on the artificial lighting load therefore, the artificial lighting load result was omitted.

3.1. Evaluation of cooling, heating, and lighting energies in relation to solar radiation in Riyadh

Figure 10 reports the total annual cooling, heating, and lighting energy consumption in Riyadh compared to the reference window. The figure clearly shows that the PDLC window reduced the total annual cooling, heating, and lighting loads compared to the reference window for all the control variables. The highest total annual cooling, heating, and lighting reduction in Riyadh climate were achieved at 100 W/m^2 with a primary energy reduction of 8.1 %. However, in Riyadh energy reduction amount decreased as the setpoint of solar radiation variables increased, which indicated more energy required for cooling during the summer months. Additionally, the PDLC was able to control the solar radiation transmission and reduce the annual energy consumption at the highest solar radiation setpoint 1000 W/m^2 by 5.2 %. Table 5 presents the results of the annual energy usage in Riyadh. The results show the cooling load increased over all solar radiation thresholds reflecting the importance of air conditioning in the summer months when electricity usage is double of that in the winter months [42]. The heating load increased when the solar radiation was set to 100 W/m^2 and 250 W/m^2 due to low solar radiation level in Riyadh. However, when PDLC window was controlled at 500 W/m^2 and higher solar radiation level the heating demand decreased, which indicated less need for heating system.

Figure 11 shows the total monthly cooling, heating, and lighting energy consumption in Riyadh. The PDLC window was able to control the solar radiation at various setpoints and had an excellent impact on reducing the cooling load during the summer months. When the PDLC was controlled to change its transparency from transparent to translucent at 100 W/m^2, it achieved 12.7 % of cooling load reduction during the summer. However, there was no heating load reduction due to Riyadh's weather pattern, which is cooling dominated. Table 6 reports the monthly energy consumption in Riyadh in relation to solar radiation against the reference window.

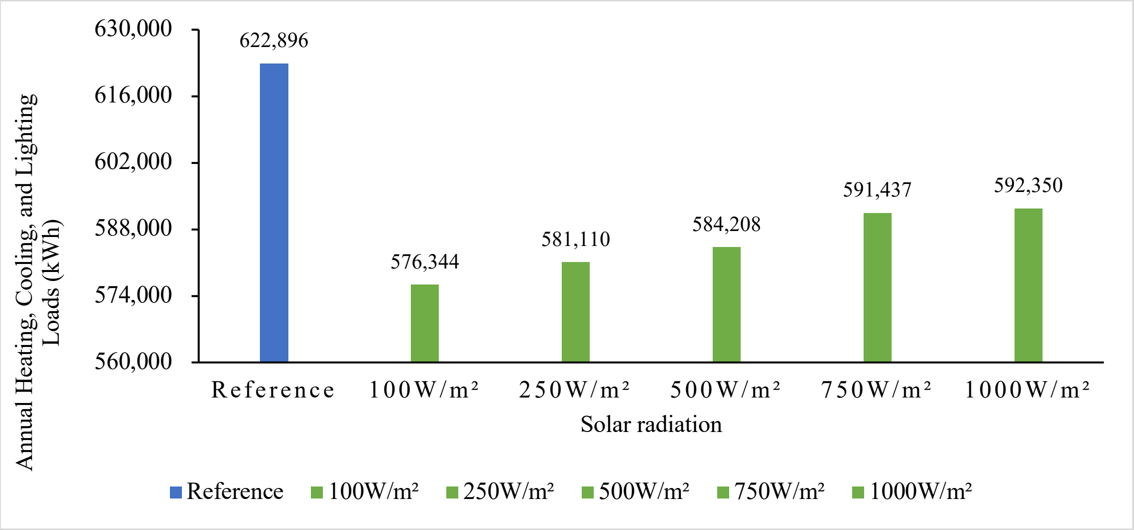

Figure 10. Total annual cooling, heating, and lighting energy consumption in relation to solar radiation in Riyadh. The graph illustrates the performance of PDLC glazing at various solar radiation intensities (green bars) compared to the reference window (blue bar).

Table 5. The total annual energy consumption in Riyadh in relation to solar radiation.

Energy (kWh)	**100 W/m^2**	**250 W/m^2**	**500 W/m^2**	**750 W/m^2**	**1000 W/m^2**	**Reference**
Cooling	368222	372854	376198	383293	384216	415019
Heating	4374	4508	4261	4396	4385	4128
Total Energy	576344	949456	584208	591437	592350	622896

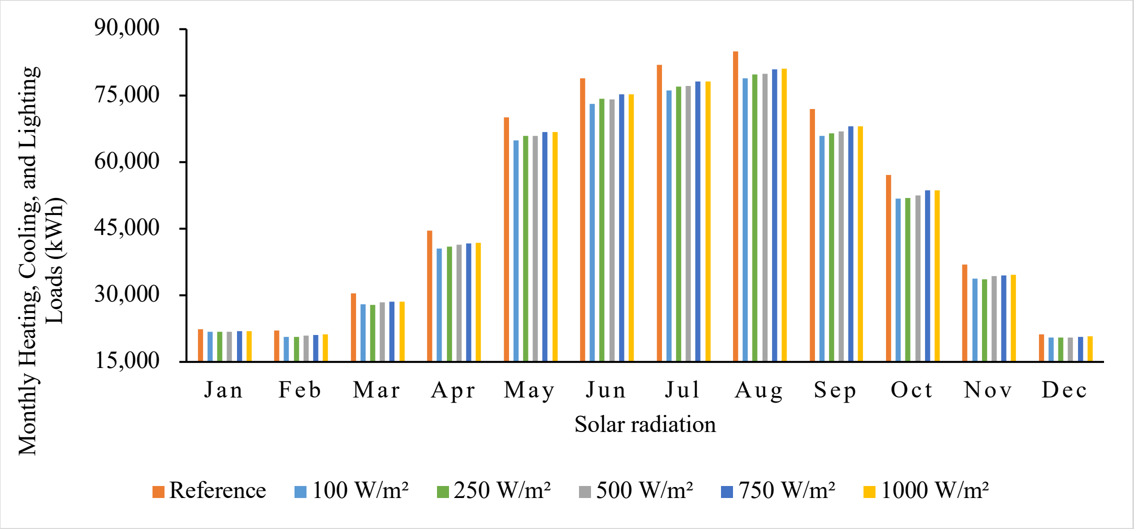

Figure 11. Total monthly cooling, heating, and lighting energy consumption in relation to solar radiation in Riyadh. The graph shows the performance of the PDLC window at various solar radiation intensities (light blue, green, grey, dark blue, and yellow bars) compared to the reference window (orange bar).

Table 6. Total monthly cooling, heating, and lighting loads in relation to solar radiation in Riyadh

Months	100 W/m²	250 W/m²	500 W/m²	750 W/m²	1000 W/m²	Reference
Jan	21,756	21,742	21,745	21,872	21,970	22,375
Feb	20,690	20,700	20,880	21,125	21,176	22,081
Mar	28,044	27,899	28,492	28,543	28,613	30,461
Apr	40,609	41,039	41,441	41,741	41,913	44,528
May	64,933	65,879	65,913	66,767	66,880	70,178
Jun	73,195	74,243	74,181	75,303	75,339	78,903
Jul	76,131	77,103	77,235	78,172	78,177	81,983
Aug	78,972	79,818	79,980	80,956	81,032	84,975
Sep	65,904	66,510	66,979	68,116	68,141	72,005
Oct	51,790	51,947	52,510	53,665	53,670	57,210
Nov	33,836	33,685	34,297	34,498	34,663	36,991
Dec	20,485	20,546	20,555	20,678	20,775	21,205

3.2. Evaluation of cooling, heating, and lighting energies in relation to solar radiation in London

Figure 12 presents the data analysis of the PDLC window against the reference window for the total annual cooling, heating, and lighting loads in London. From the total annual energy consumption results, the PDLC window performed better in saving energy than the reference window through all the solar radiation variables. It was found that in London lowest annual energy saving was 1.2 % at 500 W/m^2. The annual energy amount decreased at 100 W/m^2, and 250 W/m^2, which was lower than 500 W/m^2 due to more heating required at lower solar radiation level. Figure 13 shows the monthly energy consumption in London in relation to solar radiation as well as the monthly energy saving compared to the reference window. As cold is a dominant weather condition in London, the PDLC window decreased the monthly heating loads during the winter months under all solar radiation setpoints. When the solar radiation variables were set to 500 W/m^2 and 1000 W/m^2, the PDLC window decreased the heating loads by 4.9 % and 4.2 %, respectively. Table 7 reports the results of the annual energy consumption in London. Table 8 reports the monthly energy consumption in London in relation to solar radiation for the PDLC window and reference window.

Analysis showed that the PDLC window controlled by various solar radiation variables, was found that the lowest energy saving was at 100 W/m^2 and 500 W/m^2 in Riyadh and London, respectively. In comparison, Riyadh had a reduction in the annual cooling load by 12.7% at 100 W/m^2, which was the most significant effect, unlike London had a 4.9 % heating load decrease at 500 W/m^2. Therefore, the PDLC window demonstrated better performance in cooling-based weather condition than heating-based weather condition. The results suggest that controlling the PDLC window at 100 W/m^2 for Riyadh (arid climate zone) would improve energy efficiency.

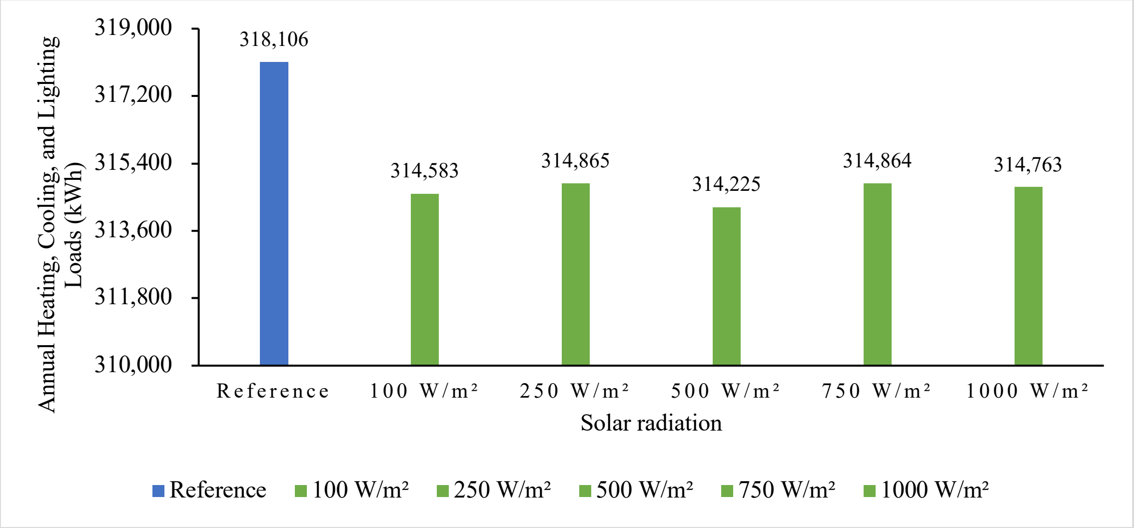

Figure 12. Total annual cooling, heating, and lighting energy consumption in relation to solar radiation in London. The graph illustrates the performance of the PDLC glazing at various solar radiation intensities (green bars) compared to the reference window (blue bar).

Table 7. The total annual energy consumption in London in relation to solar radiation.

Energy (kWh)	100 W/m^2	250 W/m^2	500 W/m^2	750 W/m^2	1000 W/m^2	Reference
Cooling	10962	10999	11768	11710	11656	10830
Heating	99872	100117	98709	99406	99360	103528
Total Energy	314583	314865	314225	314864	314763	318106

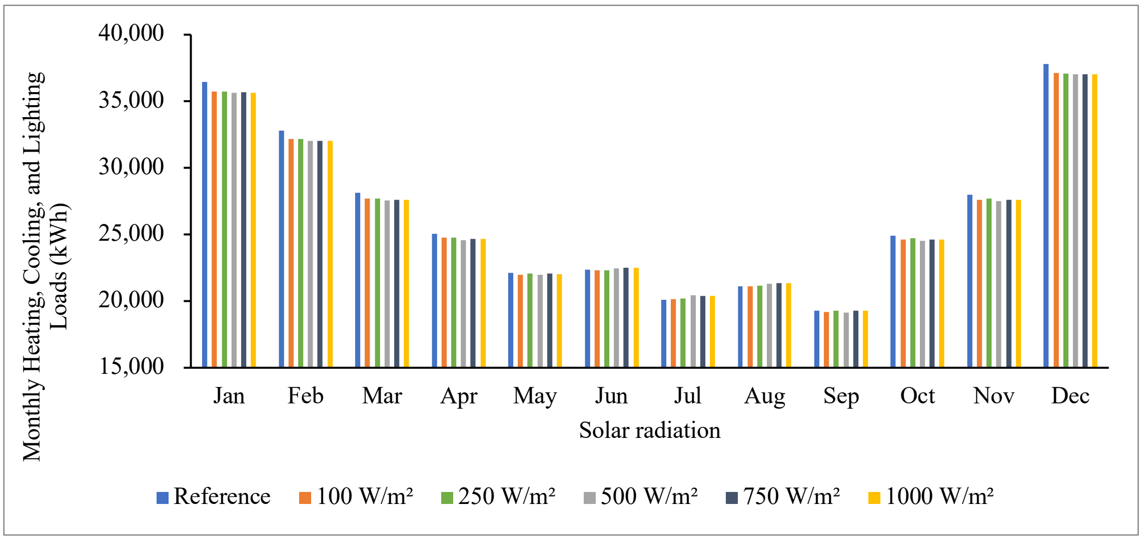

Figure 13. Total monthly cooling, heating, and lighting energy consumption in relation to solar radiation in London. The graph shows the performance of the PDLC window at various solar radiation intensities (light blue, green, grey, dark blue, and yellow bars) compared to the reference window (orange bar).

Table 8. Total monthly cooling, heating, and lighting energies in relation to solar radiation in London

Months	100 W/m²	250 W/m²	500 W/m²	750 W/m²	1000 W/m²	Reference
Jan	35,745	35,748	35,654	35,667	35,654	36,453
Feb	32,183	32,150	32,047	32,040	32,029	32,796
Mar	27,717	27,704	27,553	27,605	27,598	28,111
Apr	24,751	24,768	24,563	24,673	24,671	25,046
May	21,997	22,050	21,962	22,052	22,039	22,124
Jun	22,334	22,308	22,454	22,496	22,485	22,357
Jul	20,146	20,222	20,448	20,409	20,382	20,125
Aug	21,134	21,149	21,302	21,370	21,353	21,131
Sep	19,204	19,277	19,160	19,277	19,286	19,285
Oct	24,630	24,727	24,514	24,638	24,635	24,896
Nov	27,626	27,688	27,529	27,610	27,604	27,972
Dec	37,115	37,073	37,038	37,027	37,027	37,810

3.3. Evaluation of cooling, heating, and lighting energies in relation to outdoor temperature in Riyadh

Figure 14 shows that the total annual energy saving for the PLDC window compared to the reference window. The energy decrease was the highest at the minimum temperature 4 °C with an 8.1% energy reduction in the total annual cooling, heating, and lighting loads. As Riyadh reached the maximum air temperature 46 °C, the total annual energy reduction dropped to 5.2%, indicating that outdoor temperature influences the indoor climate and more cooling energy is required. Even though the energy saving at maximum temperature 46 °C decreased, the PDLC window reduced the cooling load compared to the reference window as shown in Table 9.

Figure 15 shows that the amount of monthly energy saving during the summer months for the PDLC window is higher than the reference window. From the graph, during the summer months, the PDLC window reduced the cooling loads due to the switching behaviour of the PDLC. The most significant annual cooling loads reduction for the PDLC window was achieved at the minimum temperature 4 °C, and the cooling reduction was 12.8 %. In comparison, the PDLC window had a slightly better performance using the outdoor temperature control variables than the solar radiation. Table 10 shows the values of the monthly energy consumption in Riyadh in relation to outdoor temperature.

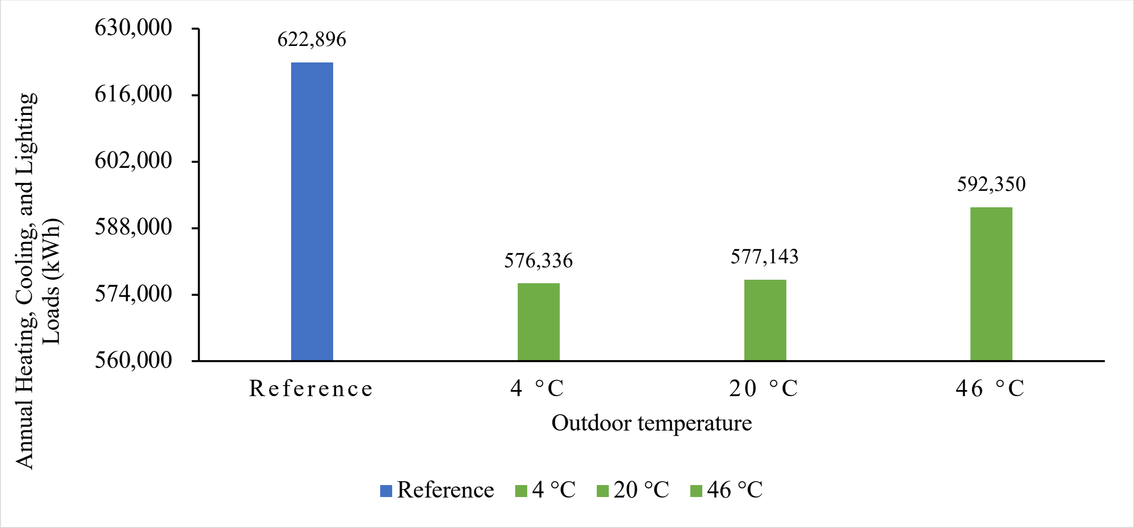

Figure 14. Total annual cooling, heating, and lighting energy consumption in relation to outdoor temperature in Riyadh. The graph illustrates the performance of the PDLC glazing at various outdoor temperatures (green bars) compared to the reference window (blue bar).

Table 9. The total annual energy consumption in Riyadh in relation to outdoor temperature.

Energy (kWh)	4 °C	20 °C	46 °C	Reference
Cooling	367979	368991	384216	415019
Heating	4609	4404	4385	4128
Total Energy	576336	577143	592350	622896

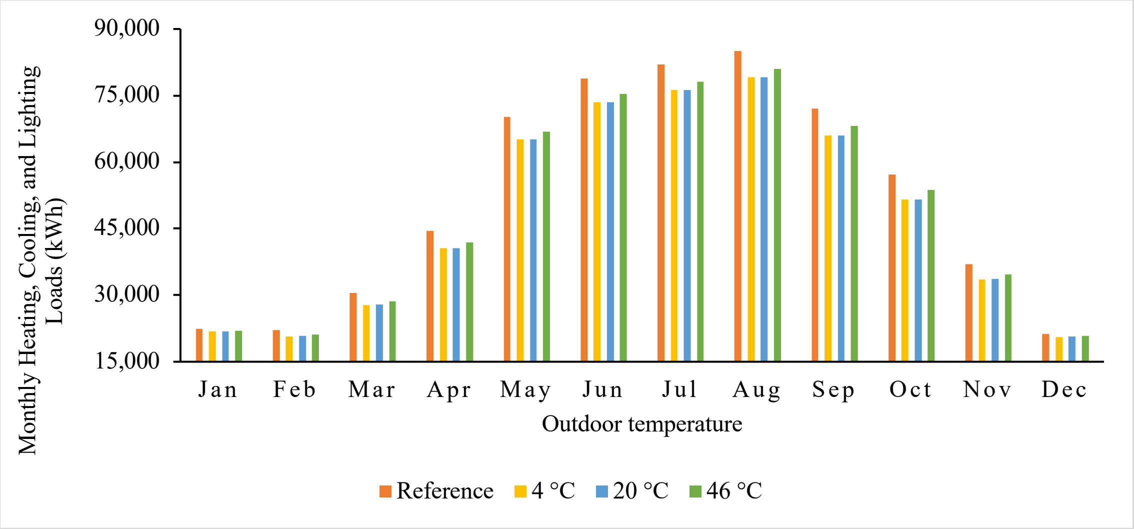

Figure 15. Total monthly cooling, heating, and lighting energy consumption in relation to outdoor temperature in Riyadh. The graph shows the performance of the PDLC window at various outdoor temperatures (yellow, light blue, and green bars) compared to the reference window (orange bar).

Table 10. Total monthly cooling, heating, and lighting energy consumption in relation to outdoor temperature in Riyadh

Months	4 °C	20 °C	46 °C	Reference

Jan	21,790	21,911	21,970	22,375
Feb	20,657	20,838	21,176	22,081
Mar	27,714	27,887	28,613	30,461
Apr	40,558	40,614	41,913	44,528
May	65,124	65,124	66,880	70,178
Jun	73,446	73,446	75,339	78,903
Jul	76,275	76,275	78,177	81,983
Aug	79,155	79,155	81,032	84,975
Sep	66,011	66,011	68,141	72,005
Oct	51,587	51,625	53,670	57,210
Nov	33,482	33,625	34,663	36,991
Dec	20,538	20,632	20,775	21,205

3.4. Evaluation of cooling, heating, and lighting energies in relation to outdoor temperature in London

Figure 16 shows an annual energy decrease for the PDLC window in comparison to the reference window under all control condition variables. Unlike Riyadh, the PDLC window best performance in London was not at the minimum temperature, but rather at 20 °C. The results show that the PDLC window achieved a 1.3% reduction in the total annual cooling, heating, and lighting loads at 20 °C. This performance was attributed to the decreased in heating loads at 20 °C, and contrastingly higher demand for heating energy was required at the minimum temperature as can be seen in Table 11.

Figure 17 shows that the reduction of the heating loads of the PDLC window from January to April was higher compared to the reference window. Controlling the PDLC window with outdoor temperature yielded 4.2% of heating loads reduction at 20 °C. During the summer months, the PDLC window had slightly better performance than the reference window, particularly when the PDLC window was controlled to switch to translucent state at 20 °C. The cooling and heating loads during the summer months are minimal due to the moderate weather conditions in London. Table 12 shows the values of the monthly energy consumption in London in relation to outdoor temperature.

The results demonstrate that Riyadh and London had the lowest annual energy reduction at 4 °C and 20 °C, respectively. Specifically, Riyadh's best performance was seen with a reduction of 12.8% in its annual cooling loads, whilst London decreased the annual heating loads by 4.2%. The highest energy reduction was achieved in Riyadh when the PDLC window was controlled by outdoor temperature. On the contrary, the highest energy decrease in London was when solar radiation was used as a control condition variable. Therefore, it can be deduced that outdoor temperature control for the PDLC window is more effective in Riyadh (arid climate) in regard to the cooling, heating, and lighting energy, than in London (temperate climate).

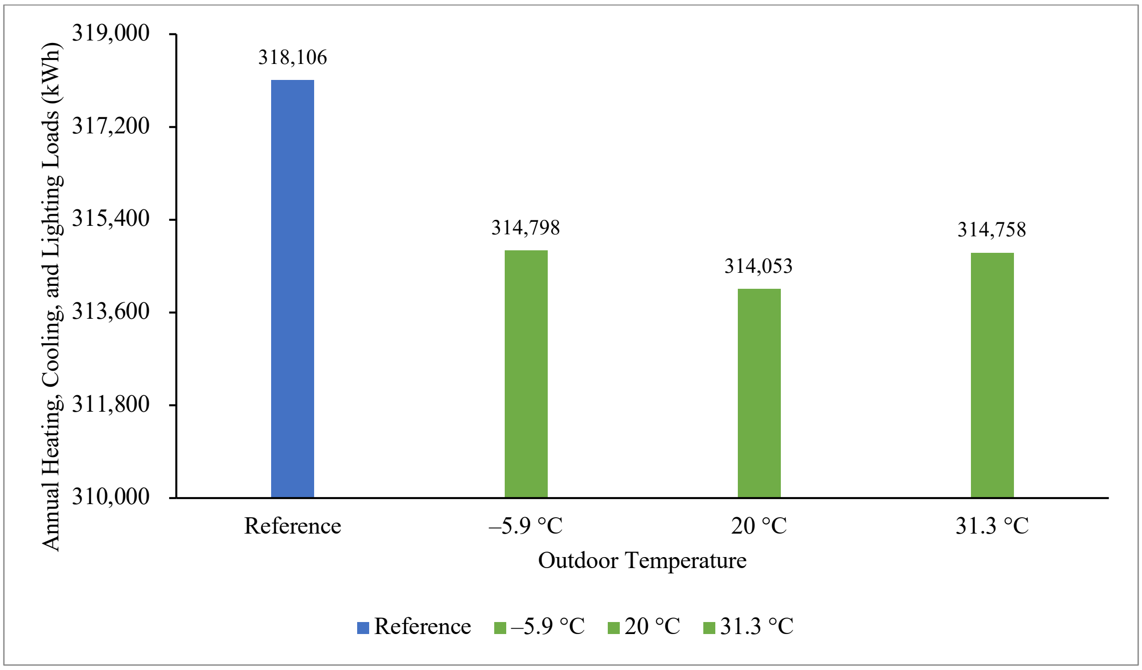

Figure 16. Total annual cooling, heating, and lighting energy consumption in relation to outdoor temperature in London. The graph illustrates the performance of the PDLC glazing at various outdoor temperatures (green bars) compared to the reference window (blue bar).

Table 11. The total annual energy consumption in London in relation to outdoor temperature.

Energy (kWh)	**–5.9 °C**	**20 °C**	**31.3 °C**	**Reference**
Cooling	10927	10920	11650	10830
Heating	100123	99385	99360	103528
Total Energy	314798	314053	314758	318106

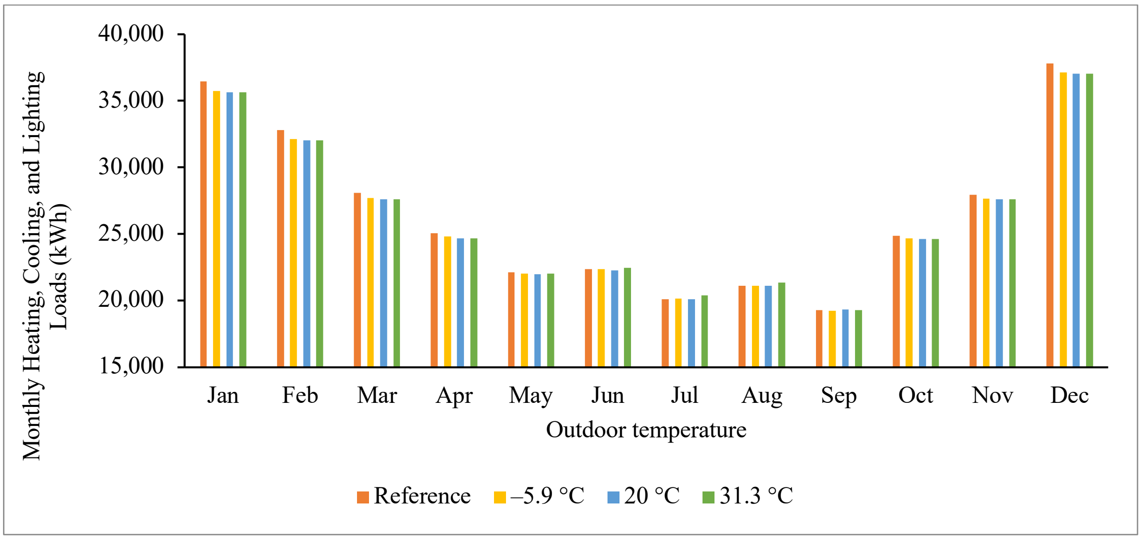

Figure 17. Total monthly cooling, heating, and lighting energy consumption in relation to outdoor temperature in London. The graph shows the performance of the PDLC window at various outdoor temperatures (yellow, light blue, and green bars) compared to the reference window (orange bar).

Table 12. Total monthly cooling, heating, and lighting energies in relation to outdoor temperature in London

Months	–5.9 °C	20 °C	31.3 °C	Reference
Jan	35,726	35,654	35,654	36,453
Feb	32,155	32,029	32,029	32,796
Mar	27,730	27,598	27,598	28,111
Apr	24,825	24,671	24,671	25,046
May	22,026	21,976	22,039	22,124
Jun	22,374	22,275	22,480	22,357
Jul	20,141	20,112	20,382	20,125
Aug	21,128	21,140	21,353	21,131
Sep	19,235	19,323	19,286	19,285
Oct	24,686	24,644	24,635	24,896
Nov	27,648	27,604	27,604	27,972
Dec	37,123	37,027	37,027	37,810

3.5. Daylight performance of PDLC window in Riyadh in relation to solar radiation

One of the objectives of the smart windows is to control solar radiation in order to provide visual comfort. Therefore, OpenStudio component was utilised to evaluate the daylight performance using the same shading control strategy used for energy evaluation. The daylight glare index value (DGI) for an office building is suggested as 22 for acceptable DGI [73]. The DGI values were recorded hourly for an entire year, and the interior illuminance was set to dim to 300 lux when there is enough daylight. The interior illuminance and DGI were evaluated for three daylight zones, high, intermediate, and low daylight zone.

Figure 18 reports the results of the percentage of annual DGI of the PDLC window in Riyadh. In general, The PDLC window performance in all three daylight zones and solar radiation thresholds was higher than the reference window. In the low daylight zone, the PDLC window was able to control the glare at 100 W/m^2 only by 24.2% during the year, while 75.8% of the DGI value was above 22. However, in the case of the reference window, the DGI value above 22 was 89.28% during the year for the low daylight zone. It is clear from the graph that the higher the solar radiation, the higher the DGI value was in the low daylight zones. For the intermediate and high daylight zones, the DGI value above 22 was 90.14% and 90.67%, respectively for the PDLC window in all solar radiation thresholds. For the reference window, the DGI value above 22 was 90.39% and 90.80% during the year for the intermediate and high daylight zones, respectively. Table 13 shows the results of the percentage of annual DGI above 22 in Riyadh.

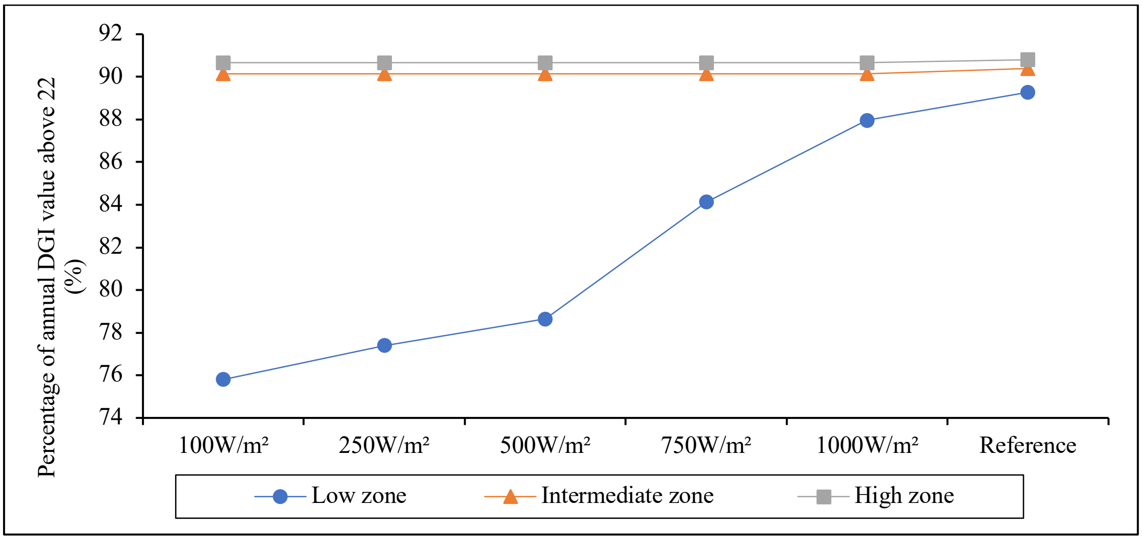

Figure 18. Percentage of annual daylight glare index above 22 in relation to solar radiation in Riyadh.

Table 13. Percentage of annual daylight glare index (DGI) in Riyadh in relation to solar radiation

	The percentage of annual DGI above 22 (%)					
Daylight Zone	100W/m²	250W/m²	500W/m²	750W/m²	1000W/m²	Reference
Low zone	75.80	77.40	78.65	84.13	87.96	89.28
Intermediate zone	90.14	90.14	90.14	90.14	90.14	90.39
High zone	90.67	90.67	90.67	90.67	90.67	90.80

Figure 19 shows the results of the interior illuminance comfort in Riyadh in relation to solar radiation. The PDLC window offered the best interior illuminance in the low daylight zone at 750 W/m^2 compared to the reference window, while the lowest performance was in the high daylight zone at 1000 W/m^2. When solar radiation was set to 100 to 500 W/m^2, the PDLC window performed better in the intermediate daylight zone than in the low daylight zone. In contrast, the performance of the PDLC window was higher in the low daylight zone when the solar radiation was between 750 to 1000 W/m^2 indicating that the PDLC window offers high diffuse transmission at high solar radiation. The PDLC window provided low interior illuminance comfort in the high daylight zone in all solar radiation thresholds; however, the performance was better than the reference window with the exception at 1000 W/m^2. Table 14 presents the percentage of annual illuminance at setpoint 300 lx.

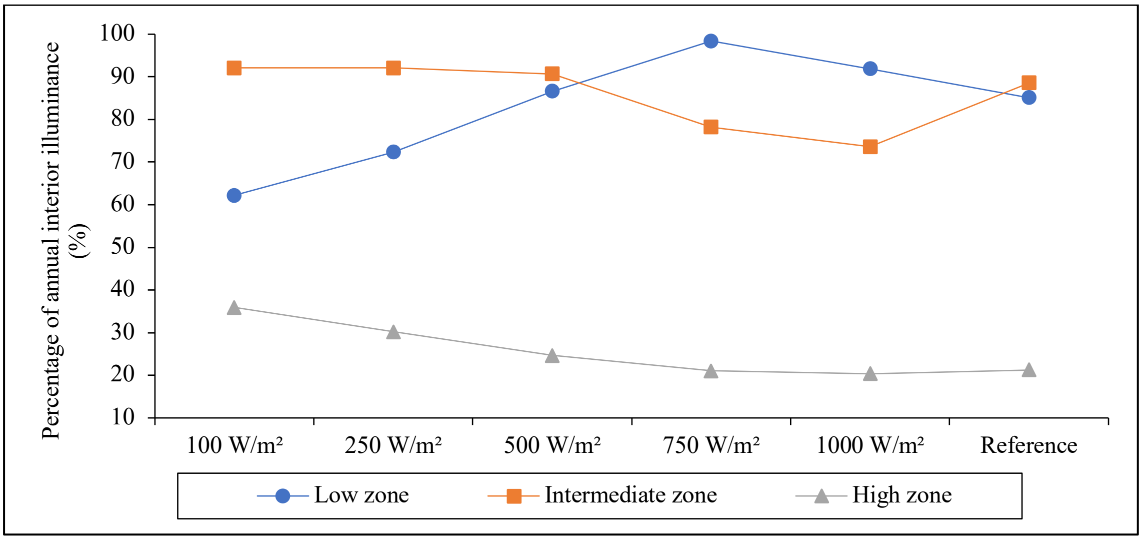

Figure 19. Percentage of annual daylight illuminance comfort in Riyadh in relation to solar radiation.

Table 14. Interior daylight illuminance in Riyadh in relation to solar radiation.

	Percentage (%) of annual illuminance at setpoint 300 lx					
	100 W/m²	250 W/m²	500 W/m²	750 W/m²	1000 W/m²	Reference
Low zone	62.22	72.36	86.64	98.41	91.89	85.10
Intermediate zone	92.12	92.12	90.66	78.23	73.63	88.61
High zone	35.93	30.21	24.62	21.02	20.35	21.26

3.6. Daylight performance of PDLC window in London relation to solar radiation

Figure 20 illustrates the results of the percentage of annual DGI of the PDLC window in London in relation to solar radiation. The best performance of the PDLC window for controlling the glare during the year was in the low daylight zone at 100 W/m^2. In addition, glare was reduced by the PDLC window by 36.94% compared to the reference window which controlled the glare by 34.45% during the year in the low daylight zone. The performance of the PDLC window to control the glare was reducing as the solar radiation was increasing. The annual percentage of the DGI for the PDLC window was almost similar in the intermediate and high daylight zone and was higher than the reference window. The results of the annual percentage of DGI were the same in the intermediate and high daylight zone regardless of the amount of solar radiation. Daylight illuminance is a variable parameter and generally diminishes as the distance from the window increases. Thus, the data analysis showed that all high daylight zones exhibited high daylight illuminance due to the close distance between the window and the daylight reference point (see Table 15).

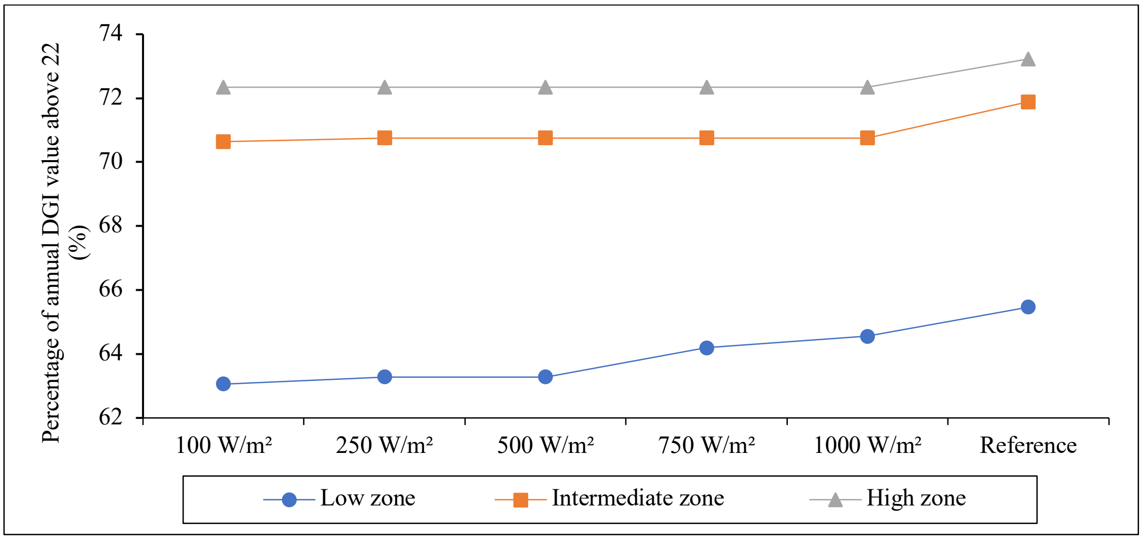

Figure 20. Percentage of annual daylight glare index in London in relation to solar radiation.

Table 15. Exceeded hours of DGI above 22 in London in relation to solar radiation.

	The percentage of annual DGI above 22 (%)					
Daylight Zone	100 W/m²	250 W/m²	500 W/m²	750 W/m²	1000 W/m²	Reference
Low zone	63.06	63.28	63.28	64.19	64.55	65.46
Intermediate zone	70.64	70.75	70.75	70.75	70.75	71.89
High zone	72.34	72.34	72.34	72.34	72.34	73.23

Figure 21 shows the results for the interior illuminance for the PDLC window in London. The PDLC window delivered an excellent performance for providing adequate interior illuminance in the intermediate daylight zone by 96.44 at 750 W/m^2. In general, the daylight performance of the PDLC window was acceptable in all daylight zones, except for the high daylight zone. The data analysis of the interior illuminance showed that the performance of the PDLC window was improving as the amount of solar radiation was getting higher. The daylight performance of the PDLC window was higher compared to the reference window in both the intermediate and low daylight zones at 500 W/m^2, 750 W/m^2, and 1000 W/m^2. The lowest daylight performance of the PDLC window was in the high daylight zone due to the small distance between the daylight zone and the window. However, the PDLC window provided better interior illuminance in comparison to the reference window, particularly at 100 W/m^2 as can be seen in Table 16.

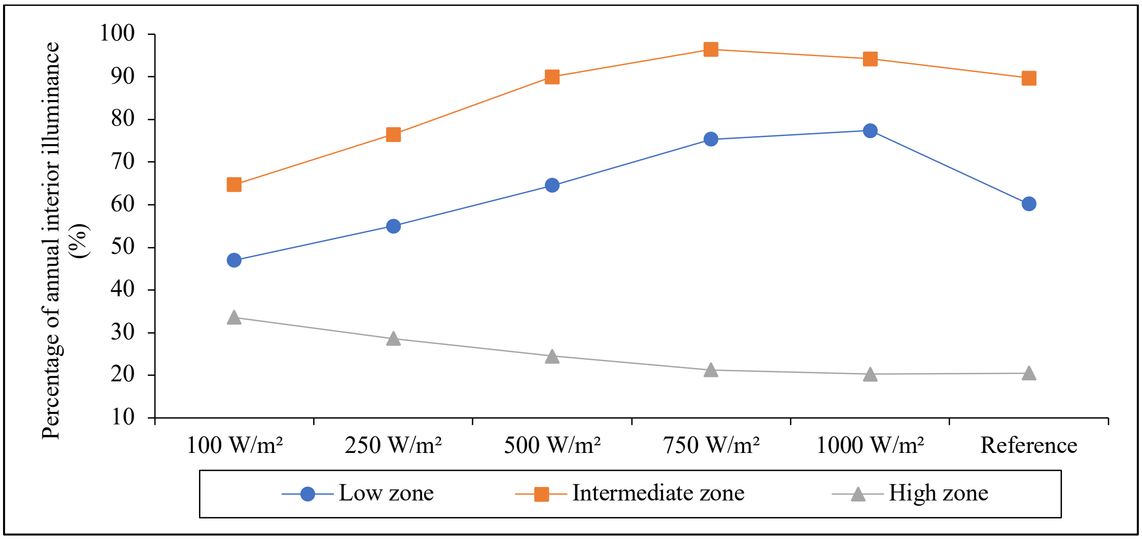

Figure 21. Percentage of annual daylight illuminance comfort in London in relation to solar radiation.

Table 16. Percentage of annual daylight illuminance comfort in London in relation to solar radiation.

	Percentage (%) of annual illuminance at setpoint 300 lx					
Daylight Zone	100 W/m²	250 W/m²	500 W/m²	750 W/m²	1000 W/m²	Reference
Low zone	46.98	55.03	64.57	75.33	77.42	60.18
Intermediate zone	64.73	76.46	90.02	96.44	94.20	89.71
High zone	33.55	28.64	24.50	21.26	20.29	20.53

3.7. Daylight performance of PDLC window in Riyadh in relation to outdoor temperature

Figure 22 reports the results of the annual DGI in Riyadh with respect to outdoor temperature. The graph shows that the performance of the PDLC window in controlling the annual DGI exceeded the reference window performance in all daylight zones. The percentage of annual DGI above 22 increased as the outdoor temperature was going higher when the PDLC window was employed due to the increase in the amount of solar radiation. The PDLC window achieved the best performance in the low daylight zone with 68.53% of the annual DGI above 22 at 4 °C. Table 17 shows that the PDLC window performance reduced in the intermediate and high daylight zones due to the short distance to the window, indicating higher solar radiation transmission. In addition, the PDLC window demonstrated a higher performance compared to the reference window in the intermediate and high daylight zones, particularly at 4 °C.

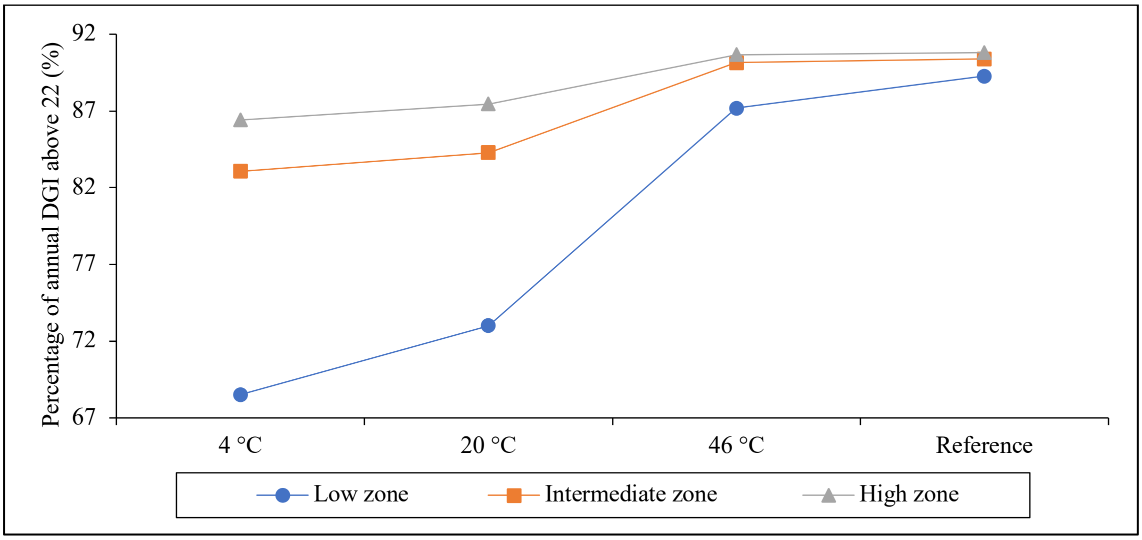

Figure 22. Percentage of annual daylight glare index in Riyadh in relation to outdoor temperature.

Table 17. Percentage of annual daylight glare index in Riyadh in relation to outdoor temperature.

	The percentage of annual DGI above 22 (%)			
Daylight Zone	4 °C	20 °C	46 °C	Reference
Low zone	68.52	73.00	87.18	89.28
Intermediate zone	83.06	84.27	90.14	90.39
High zone	86.41	87.46	90.67	90.80

Figure 23 illustrates the results of the interior illuminance of the PDLC window in Riyadh. The PDLC window achieved the best performance in the intermediate and low daylight zones by 93.09% at 20 °C and 91.89% at 46 °C by, respectively. When the PDLC window was utilised in the low light zone, the interior illuminance improved as the outdoor temperature increased. The quality of the interior illuminance of the PDLC window reduced in the intermediate daylight zone at 46 °C, indicating that a high amount of solar radiation was transmitted. It is clear from the graph that the interior illuminance of the PDLC window in the high daylight zone decreased as the outdoor temperature increased. Table 18 reports the results of the percentage of annual daylight illuminance comfort in Riyadh

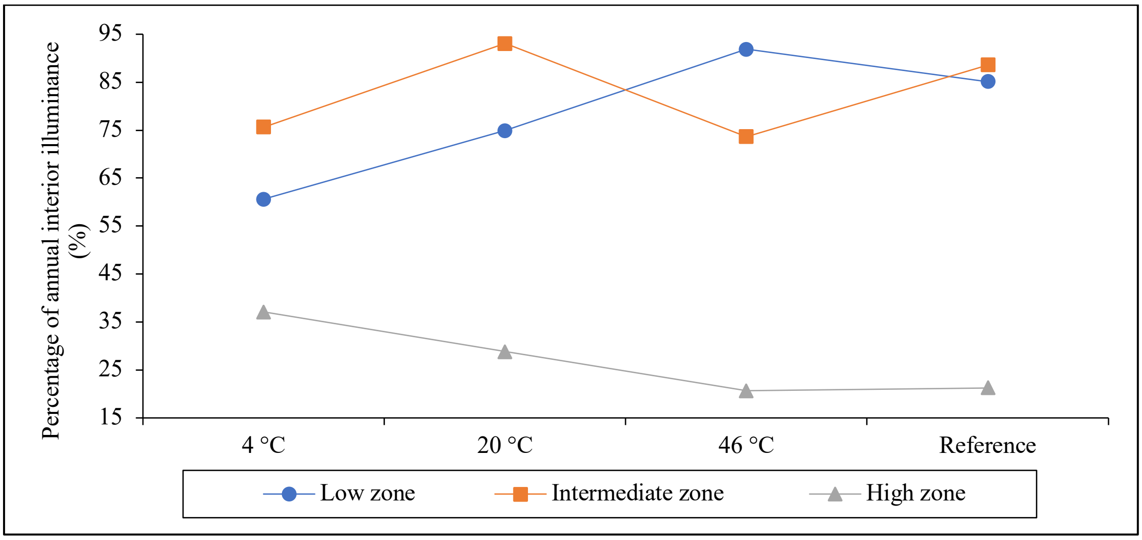

Figure 23. Percentage of annual daylight illuminance comfort in Riyadh in relation to outdoor temperature.

Table 18. Percentage of annual daylight illuminance comfort in Riyadh in relation to outdoor temperature.

	Percentage (%) of annual illuminance at setpoint 300 lx			
Daylight Zone	4 °C	20 °C	46 °C	Reference
Low zone	60.62	74.92	91.89	85.10
Intermediate zone	75.66	93.09	73.63	88.61
High zone	37.11	28.78	20.68	21.26

3.8. Daylight performance of PDLC window in London in relation to outdoor temperature

Figure 24 reports the results of the annual DGI in London. The performance of the PDLC window exceeded the reference window's performance in all daylight zones and all outdoor temperature thresholds. The best performance achieved by the PDLC window was in the low daylight zone by 55.09% at -5.9 °C. The percentage of annual DGI decreased as the outdoor temperature increased when the PDLC window was employed in all daylight zones (see Table 19). The PDLC showed similar behaviour in Riyadh and London when the solar radiation control was used. In the intermediate daylight zone, the PDLC window showed similar performance with the low daylight zone at -5.9 °C by 57.36%. The percentage of annual DGI decreased in the PDLC window after -5.9 °C for both intermediate and high daylight zones due to the high amount of solar radiation and close distance to the window.

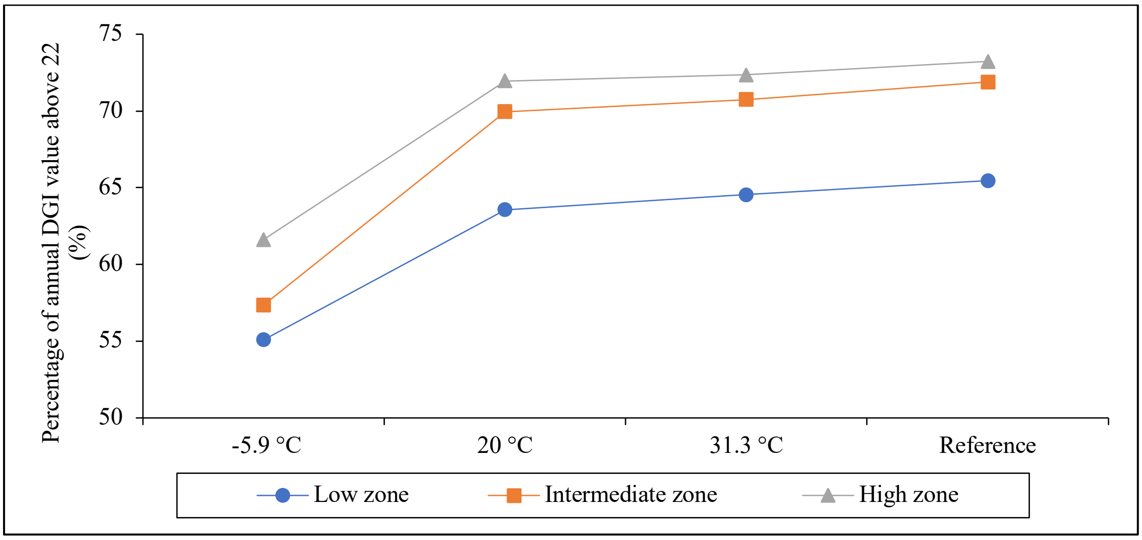

Figure 24. Percentage of annual daylight glare index in London in relation to outdoor temperature.

Table 19. Percentage of annual daylight glare index in London in relation to outdoor temperature.

	The percentage of annual DGI above 22 (%)			
Daylight Zone	-5.9 °C	20 °C	31.3 °C	Reference
Low zone	55.09	63.56	64.55	65.46
Intermediate zone	57.36	69.96	70.75	71.89
High zone	61.63	71.96	72.34	73.23

Figure 25 shows the results of the annual interior illuminance in London. The PDLC window performance was higher than the reference window in all daylight zones except at -5.9 °C in the low and intermediate daylight zones. The PDLC window achieved excellent performance by 97.77% and 94.2% in the intermediate daylight zone at 20 °C and 31.3 °C, respectively. The small distance between the window and the high daylight zone greatly affected the performance of the PDLC window. Table 20 illustrates that the low daylight zone had acceptable interior illuminance, precisely at 20 °C and 31.3 °C, indicating that the PDLC window exhibit high diffuse transmission.

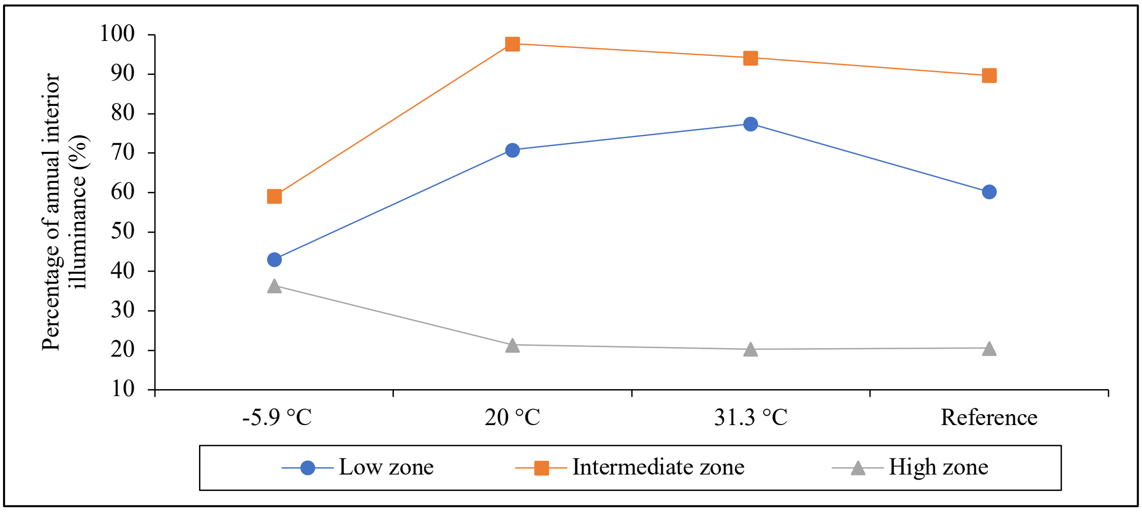

Figure 25. Percentage of annual daylight illuminance comfort in London in relation to outdoor temperature.

Table 20. Percentage of annual daylight illuminance comfort in London in relation to outdoor temperature.

	Percentage (%) of annual illuminance at setpoint 300 lx			
Daylight Zone	-5.9 °C	20 °C	31.3 °C	Reference
Low zone	43.12	70.79	77.42	60.18
Intermediate zone	59.12	97.77	94.20	89.71
High zone	36.43	21.40	20.29	20.53

4. Conclusions

In the current research, an EnergyPlus simulation study was employed to evaluate the impact of the PDLC window performance of an office building in regards to cooling, heating, and lighting loads in Riyadh, Saudi Arabia (arid climate), and London, United Kingdom (temperate oceanic climate). In addition, the annual glare percentage and interior daylight were evaluated. The control shading strategy variables used for the simulation study were solar radiation and outdoor temperature. The following conclusion can be drawn from the present study:

1. The results of this study showed that the PDLC window was able to control the solar radiation and decrease the annual cooling and heating loads under all solar radiation control variables. The current findings enhance our understanding of the PDLC window performance as it can be utilised for smart façade for buildings envelope. The PDLC window has the potential to replace shading devices such as curtains and blinds which require extensive maintenance. The results showed that the investigated PDLC window had the best performance to decrease the annual energy consumption in relation to solar radiation at 100 W/m^2 and 500 W/m^2 in Riyadh and London, respectively. The highest cooling load reduction was 12.7% in Riyadh, while the greatest heating load decrease was in London by 4.9%. Analysis that the PDLC window is more effective in Riyadh (arid climate) than London (temperate climate).
2. The results of controlling the PLDC window by outdoor temperature variables showed that the PDLC window reduced the annual cooling load by 12.8% at the minimum temperature of 4 ºC in Riyadh. In London, the annual heating load reduction was 4.2% when the PDLC window was controlled at 20 ºC. The results indicate that the outdoor temperature control strategy was more influential in Riyadh than in London.
3. The daylight performance of the PDLC window was evaluated and compared against a reference window using solar radiation control. The results showed that the PDLC window performed best in Riyadh’s low daylight zone, while the intermediate daylight zone was

the best performance for the PDLC window in London. The PDLC window achieved 75.8% and 63.06% of annual DGI during the year at 100 W/m^2 in both cities when solar radiation control was used. In addition, the PDLC window offered the best interior illuminance performance in the low daylight zone at 750 W/m^2 in Riyadh. In London, the best interior illuminance achieved in the intermediate daylight zone at 750 W/m^2.

4. Outdoor temperature was utilised to control the PDLC window and evaluate the daylight performance. The PDLC window achieved 68.52% of annual DGI above 22 during the year at 4 °C in the low daylight zone in Riyadh. While in London, the PDLC window achieved 55.09% of annual DGI in the same daylight zone. In terms of interior illuminance, the PDLC window showed the highest performance in two different daylight zones. In Riyadh, the highest interior illuminance achieved was in the low daylight zone at 46 °C while, in London was in the intermediate daylight zone at 20 °C.

This investigation was undertaken to assess the energy and daylight performance of the PDLC window in only two contrasting climate zones of Riyadh, Saudi Arabia, and London, United Kingdom. It developed an analysis model and limited its utilisation exclusively to office buildings. However, the optimal control results from the analysis are not to be standardised, as the investigated climate zones were limited only to arid and temperate oceanic weather conditions. In addition, the results do not indicate whether the optimal control conditions, as the research shows, can be applied to all type of buildings. Therefore, an investigation of PDLC window control would benefit from analysis in more diverse climate zones. Further investigation of the PDLC window in comparison with highly energy efficient windows incorporated with shading devices is suggested as a future research. This would provide a more comprehensive analysis and an analytic model that reflects a variety of building types.

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