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Building energy analysis using EC and PDLC based smart switchable window in Oman

Dashe Chidubem Iluyemi [a], Srijita Nundy [b], Saboor Shaik [c], Asif Tahir [b], Aritra Ghosh [a,*]

[a] College of Engineering, Mathematics and Physical Sciences, Renewable Energy, University of Exeter, Penryn, Cornwall TR10 9FE, UK
[b] Environmental and Sustainability Institute, University of Exeter, Penryn, Cornwall TR10 9FE, UK
[c] School of Mechanical Engineering, Vellore Institute of Technology, Vellore 632014, Tamil Nadu, India

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ABSTRACT

Worldwide energy consumption and CO_2 emissions increase yearly and the building industry contributes the most out of all the other sectors. The residential building sector of the building industry provides the largest portion of energy consumption. Reducing energy gains through elements of the building envelope such as windows is a way to combat increasing energy consumption. Smart switchable glazing can contribute to energy savings by adjusting its properties in response to user settings or an external stimulus. This study explored the potential energy savings of electrochromic (EC) and polymer disperse liquid crystal (PDLC) switchable glazing against common static window glazing for a residential building in Oman. The results showed that switchable windows displayed better optical properties than static windows, with electrochromic windows under daylight illuminance control having the highest total energy savings at 23.56% reduction compared to a single-glaze window. In a PDLC window configuration, using silver coated glass as the inner pane in the double glazing reduces energy consumption even further.

1. Introduction

Greater ownership and use of energy-consuming devices, along with fast growth in global buildings floor area, resulted in a continual increase in energy from buildings and buildings construction, accounting for over one-third of global final energy consumption (IEA, 2020). Year 2019 saw all-time high CO_2 emissions from buildings with final energy usage at around 128 EJ (up from 118 EJ in 2010), direct emissions increasing to just over 3 $GtCO_2$ (5% increase since 2010), and indirect emissions (factoring upstream power generation) accounting for 28% (10 $GtCO_2$) of energy-related emissions globally(IEA, 2020). According to the Global Status Report for Buildings and Construction 2020, the buildings and buildings construction industry is responsible for 35% of energy consumption and 38% of CO_2 emissions (see Fig. 1**)**. The report highlights buildings and buildings construction industry as the largest contributor to energy use and CO_2 emissions. Building consumes energy primarily due to maintain the thermal and visual comfort inside a building (Ghosh and Norton, 2018). Thus, energy consumption due to heating, cooling, ventilation and artificial daylight plays a crucial role in high building energy consumption (Lowe and Drummond, 2022). With the recent outbreak of COVID-19, the effect of lockdown measures, the building sector started consuming higher energy (Faulkner et al., 2022). It is evident from the different reports that changes in working patterns across the globe can have a considerable amount of enhancement of energy consumption (Nundy et al., 2021a). One of the consequences of COVID-19 is more remote work and virtual meetings (Afrianty et al., 2022). While this may not happen as frequently as it did at the height of the pandemic, this could also play a part towards sustained levels of energy consumption higher than 2019 levels.

Building consists of several envelopes and among them, windows are the most crucial one as it is thermally weak but offers a connection between building interior to exterior. While windows are important for ventilation (windows that can be opened), daylighting, and aesthetics, they can also lead to significant heat losses or gains (depending on external conditions relative to that of the acceptable conditions for comfort) if designed incorrectly (Feng et al., 2021). The main thermal and optical properties considered for windows are overall heat transfer coefficient (*U*-value), solar heat gain coefficient (SHGC), and visible transmittance ($T_{vis.}$)(Ghosh et al., 2016a, 2016b). Fig. 2 shows a window schematic and how energy transfer happens through glazing. Traditional windows have static, passive glazing technologies such as low-emissivity (low-e) (Addonizio et al., 2021), vacuum (Memon et al., 2015) (Ghosh et al., 2017a), aerogel (Mazrouei-sebdani et al., 2021),

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* Corresponding author.
E-mail address: a.ghosh@exeter.ac.uk (A. Ghosh).

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Nomenclature

EJ	Exajoule
GtCO$_2$	Gigatones of Carbon di Oxide
NCEI	National Centers for Environmental Information
NIR	Near-Infrared Radiation
SHGC	Solar Heat Gain Coefficients
U-value	Overall Heat Transfer Coefficient [Wm-2 K-1]
UDI	Useful Daylight Index

anti-reflective (Tong et al., 2021), and thermally insulated (Cerne et al., 2019). These technologies have constant optical and thermal properties. However, dynamic 'switchable' (smart) glazing modifies its optical and thermal properties based on climate-dependent variables such as heat (thermochromic) (Cao et al., 2020), light (photochromic) (Chun et al., 2021), temperature variations (thermotropic) or electricity (electrochromic, polymer dispersed liquid crystal). Photochromic and thermochromic technologies are categorised as passive smart glazing technologies as they respond in real-time to altering environmental conditions without using extra energy (Tällberg et al., 2019). Electrically activated technologies include Electrochromic (EC) (Hoon Lee et al., 2020), suspended particle device (SPD) (Ghosh et al., 2017b) and polymer dispersed liquid crystal (LC) (Shaik et al., 2022; Shaik et al., 2020). They are considered active smart glazing technologies as they can be controlled by the occupant to accommodate their needs (Nundy et al., 2021b). EC windows need direct current to become an opaque (coloured) state and without a power supply, it becomes transparent (Phan et al., 2021). The switching time of EC is higher than PDLC and SPD. SPD types need a power supply to become a transparent state and without a power supply, it is opaque (Ghosh and Norton, 2017). SPD has very low visible transmission in opaque states (Ghosh et al., 2017c). PDLC types are particularly interesting because of their higher light transmission in the opaque state (Khalid et al., 2021).

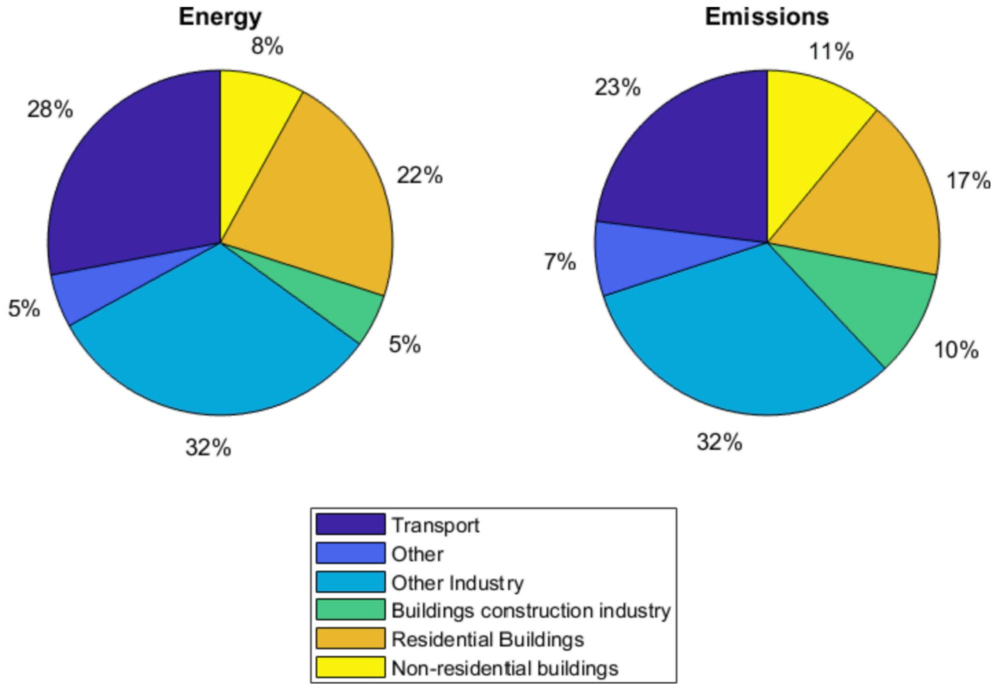

Fig. 1. Global share of energy consumption and CO$_2$ emissions by industry, 2019. Source: Global Status Report for Buildings and Construction 2020.

PDLC windows consist a PDLC film sandwiched between two transparent electrodes. An alternating current electric field is required to actuate LC molecules to change the film's state from translucent (OFF) state to a transparent (ON) state. The "ON" and "OFF" states of the PDLC films are characterised by the alignment of the particles in the film. The translucent state is represented by a misalignment of the molecules, dispersing the light whereas the transparent state is denoted by aligned molecules, allowing light to pass through (Nundy and Ghosh, 2020). Fig. 3 shows a representation of a PDLC window in its "ON" and "OFF" states. After the expiry of Raychem and KSU patents in 2002 and 2005 respectively, the industrial growth of PDLC technology took high gear (Hakemi, 2017). Previously thermal (Ghosh and Mallick, 2018a), optical (Ghosh and Mallick, 2018b), electrical (Ghosh et al., 2018a) and colour (Ghosh et al., 2018b), properties of PDLC glazing employing indoor characterisation was performed. Though PDLC is a promising technology, investigation using PDLC windows for building applications is slim. Theoretical work on PDLC for Saudi climate (Hemaida et al., 2021) was developed by using a 0.15 m × 0.14 m PDLC film which had a transmission that switched from 42% to 62% in the presence of 20 VAC supplies. This particular PDLC had SHGC 0.68 and 0.63 for the transparent and translucent state and *U*-value of 2.44 W/m^{2}K and 2.79 W/m^2 K for OFF and ON state respectively (Hemaida et al., 2020). Building energy simulation showed that the PDLC had a 12.8% cooling load reduction ability in Riyadh. To evaluate the cooling load saving potential, white, blue, pink, and yellow coloured PDLC film based windows were also investigated (Shaik et al., 2020).

The Sultanate of Oman is a country situated on the south-eastern coast of the Arabian Peninsula. Oman has seen significant population growth but with no establishment of any energy efficiency regulations, electricity consumption and peak demand have substantially increased (Krarti and Dubey, 2017). Being a developing economy, the building sector in Oman consumes 76–83% of electricity which is significantly high compared to USA building energy (Al-Saadi and Shaaban, 2019). The absence of a green building regulations code is mainly due to a lack of sustainable material utilisation in most construction projects, lack of demand for sustainable material usage, and the high cost of these sustainable construction materials (Prabhu, 2020; Safinia et al., 2017).

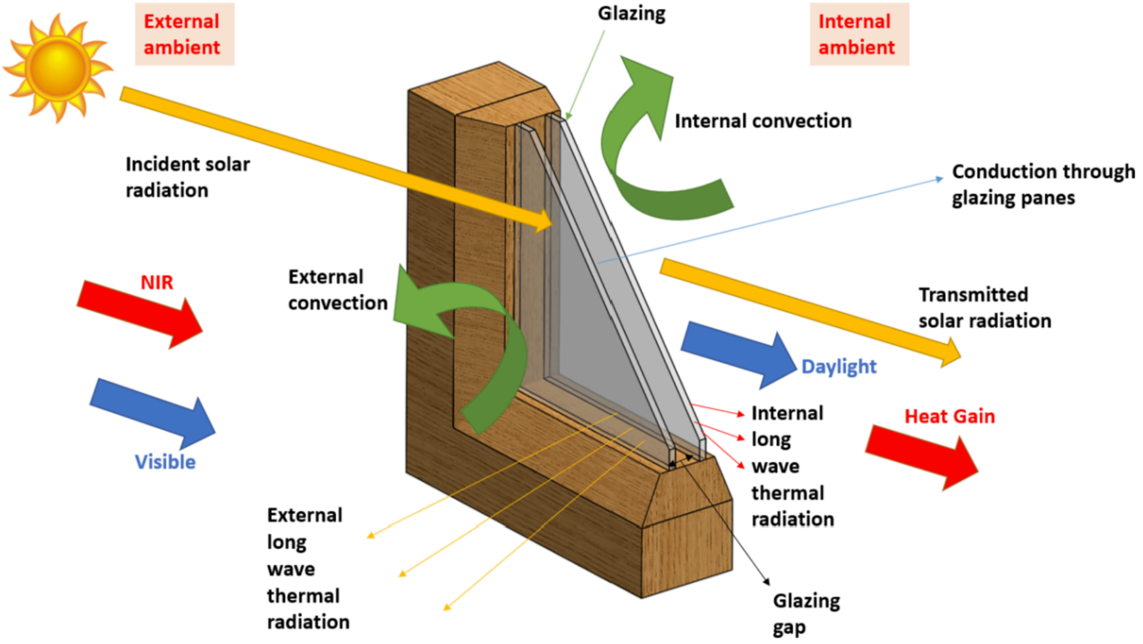

Fig. 2. Schematic of conventional double glaze system, showing heat gains and losses, and daylight penetration.

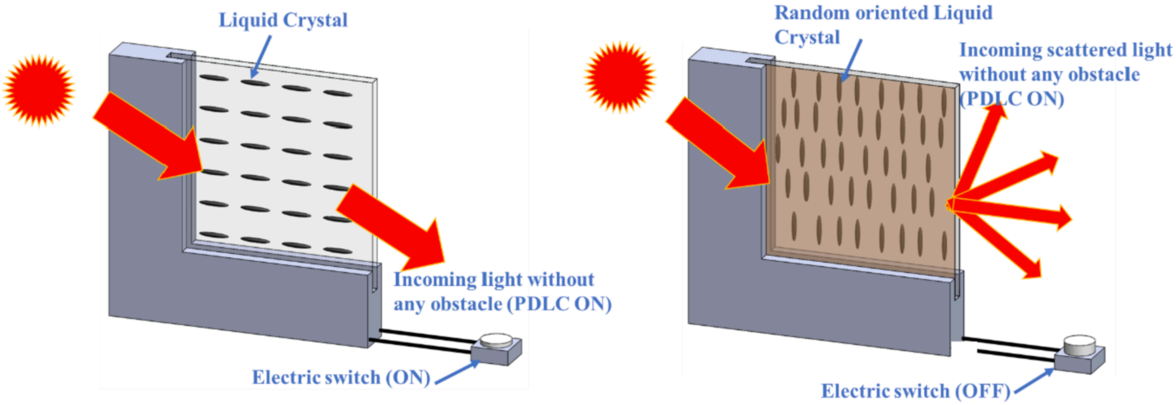

Fig. 3. Representation of PDLC in its “ON” (left) and “OFF” (right) states.

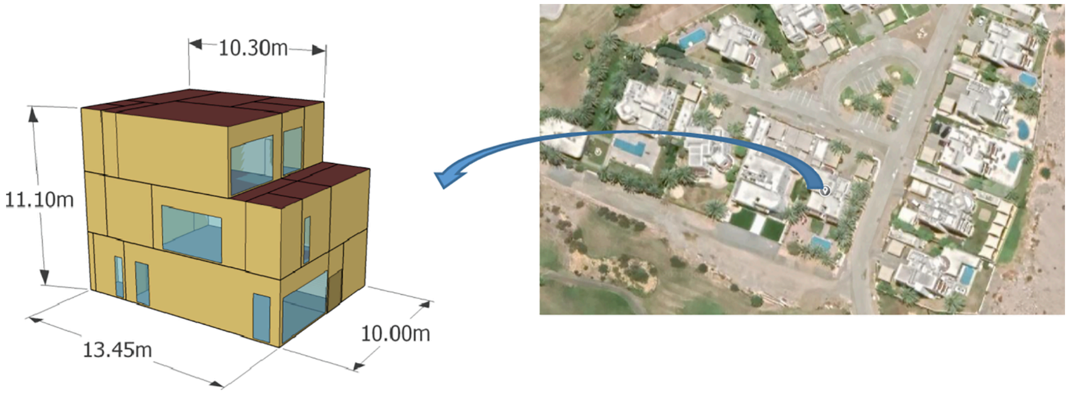

Fig. 4. (left) Prototype Villa drawn in Sketchup. The opaque elements of the house are coloured yellow and red; (right) Google Map image of the location of building model (23.57°N, 58.30°E). (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)

This, in turn, undermines Oman’s drive towards better energy efficiency and hence, reducing carbon emissions. Oman has a cooling dominated climate, classified as type 0B (extremely hot – dry) according to the American Society of Heating, Refrigerating, and Air-Conditioning Engineers Standard. Oman’s climate consists of two seasons; summer and winter. This large proportion of electricity usage taken by residential

Table 1
Screenshot of Schedule:Day:Interval objects used to define weekdays and weekends schedule for lights. Obj1 and Obj2 are object fields used by EnergyPlus to define any parameters in a class.

Field	Units	Obj1	Obj2
Name		Lights Weekday	Lights Weekend
Schedule Type Limits Name		Fraction	Fraction
Interpolate to Timestep		No	No
Time 1		07:30	07:30
Value Until Time 1	varies	0	0
Time 2		08:30	23:30
Value Until Time 2	varies	0.2	0.05
Time 3		18:00	24:00
Value Until Time 3	varies	1	0
Time 4		23:30	
Value Until Time 4	varies	0.2	
Time 5		24:00	
Value Until Time 5	varies	0	

Table 2
Summary table of all parameters considered for EnergyPlus simulations.

Parameter	Value
Building Area	332.23 m^2
Floor to ceiling height	3.7 *m*
Window aspect ratio/s	1:1.88, 1:1.6, 1:1.2, 1:0.8, 1:0.37
Window-to-wall ratio (WWR)	7.82%
Lighting	10.8 W/m^2
Illuminance set point	500 lx
Daylight Glare Index set point (DGI)	20
Ground base temperature	20 °C
HVAC cooling set point	25 °C
Operational hours	08:30–18:00 (weekdays)
Simulation time steps	6

Table 3
Optical and thermal properties of static and switchable glazing systems.

Glazing	*U*-value (W/m^2 K)	SHGC	T_{vis}	T_{sol}	Thickness (mm)
Single Glaze	3.700	0.615	0.753	0.5580	5.740
Double Glaze (w/ air)	2.013	0.538	0.674	0.4663	34.181
Double Glaze (w/ argon)	1.750	0.536	0.674	0.4663	34.181
Electrochromic - DARK	1.921	0.104	0.005	0.0020	35.260
Electrochromic - LIGHT	1.921	0.220	0.242	0.1267	35.260
PDLC (Clear Glass) - DARK	2.575	0.363	0.297	0.2409	35.440
PDLC (Clear Glass) - LIGHT	2.411	0.562	0.646	0.4700	35.440

buildings requires attention and optimisation to reduce overall electricity usage (Amoatey et al., 2022). Oman and the region are focused mainly on renewable energy resources and less attention is given to energy-saving potential and carbon emissions reduction (Alalouch et al., 2019). To meet the global energy reduction target, replacing traditional tinted low-e coated double or single glazing windows with smart switchable windows can be a potential option for Oman.

This work for the first time the building energy-saving potential was investigated by employing smart switchable PDLC type windows for a residential building in Oman. To make a robust comparison results from PDLC was compared with dynamic EC and static transparent single, air-filled double and argon filled double glazing systems. Later PDLC glazing was modified by employing clear float, low-e, and silver coated, bronze coloured, and green coloured glazing and building energy analysis was performed.

2. Methodology

2.1. Prototype building and simulation parameters

The prototype building structure was adopted from an existing 3 storey single family villa in Muscat Hills, Oman (see Fig. 4). Multi-storey single family villas are the common residential building construction in Oman (Scholz, 2021). It has a total building area of 332.23 m^2, the ground floor and first floor both have an area of 121.24 m^2 and the second floor has an area of 89.75 m^2. The ground floor has a laundry room, a living room, a bedroom, a bathroom, a washroom (i.e., a toilet), a kitchen, and a store. The first floor has two bedrooms, two bathrooms, a storeroom, and a living room. The second floor has one bedroom, one bathroom, a living room, a spare room, and a storeroom. Additionally, the building has both a staircase and an elevator. This building was drawn using Sketchup Make 2017, a 3D modelling software. Using a free and open-source extension called Euclid, Sketchup can be directly integrated with EnergyPlus, a simulation tool developed by the U.S. Department of Energy (DOE). Hence, EnergyPlus was the chosen energy simulation software.

Before using EnergyPlus to run simulations, the appropriate parameters and conditions were set. Firstly, the actual direction of the building with respect to true north was found using both Google Maps and the National Centers for Environmental Information (NCEI) magnetic field calculators. True north refers to the direction along the Earth's surface that ends at the North Pole. The direction of north on Google Maps is towards magnetic north, which refers to the direction where the Earth's magnetic field aims vertically downwards. The angle between the front face of the building and a vertical north line was estimated as 22°E by using a protractor on screen. To find the building face angle from true north, the magnetic declination at the building location was found using the NCEI declination calculator. Declination refers to the angle between magnetic and true north. The latitude and longitude at the building location were found on Google Maps and used in the declination calculator, resulting in a declination of 1.62°E. Since Oman is in the northern hemisphere, the declination has to be subtracted from the angle away from magnetic north to find the angle away from true north. That results in an estimated angle of 21.38°E.

The *U*-values for the roof and the wall were taken from EnergyPlus after the modelling was conducted and was reported to be 0.459 W/m^2 K and 1.449 W/m^2 K respectively. The prototype building model contains rooms that are entirely locked by other rooms, others without exterior windows, and others that are not occupied for long periods of time (such as stairs, elevators, and bathrooms). Therefore, the effect of altering the window construction on energy demand does not apply to these rooms and are assumed to have constant energy usage. This narrowed down the considered spaces to seven (two living rooms, four bedrooms, and a kitchen). The windows in these rooms all have different aspect ratios (length to width ratio) which are listed in Table 1 & 2. According to the information provided with the building model, the villa had 35 mm thick double-glazed windows with an air gap. The glass used in the glazing was 6 mm thick. Only the windows in these spaces were changed to investigate the resulting impact of window glazing on energy demand for the entire building. This resulted in a total conditioned window area of 61.75 m^2. The weather file for Oman's climate was not available on the EnergyPlus website and was obtained from another repository of climate data called OneBuilding (**typical meteorological years** file with data from 1979 to 2019).

2.2. Window glazing

Window glazing systems include single glazing, double glazing (with air and argon as the gap), Electrochromic, and PDLC. These systems were created in WINDOW, created by Lawrence Berkeley National Laboratory (LBNL) and then imported into EnergyPlus to conduct the simulation. Except for PDLC, other mentioned glazing systems and their

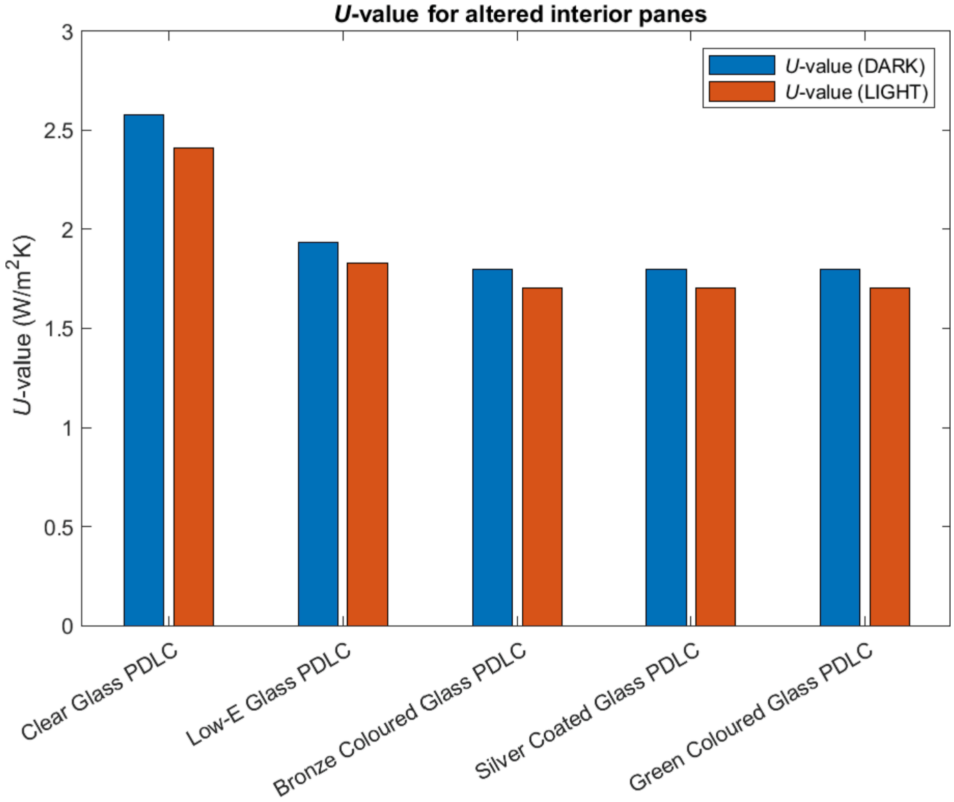

Fig. 5. Column graph showing the relationship between the U-values of the PDLC windows in their "ON" and "OFF" states for different interior panes.

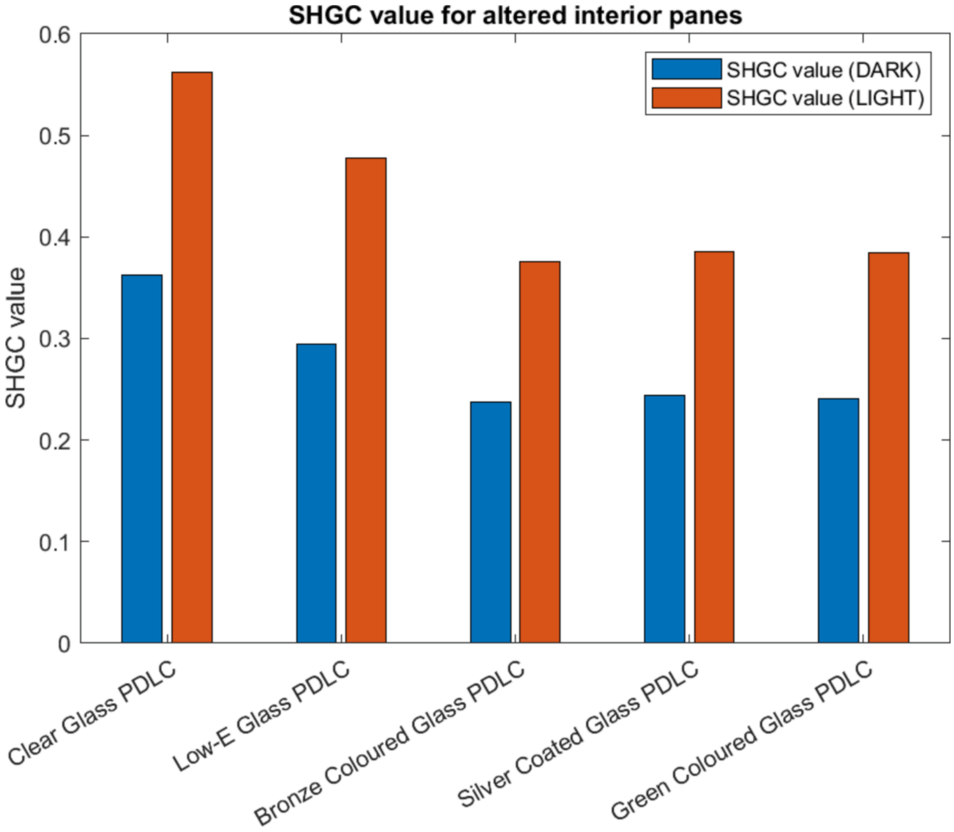

Fig. 6. Column graph showing the relationship between the SHGC of the PDLC windows in their "ON" and "OFF" states for different interior panes.

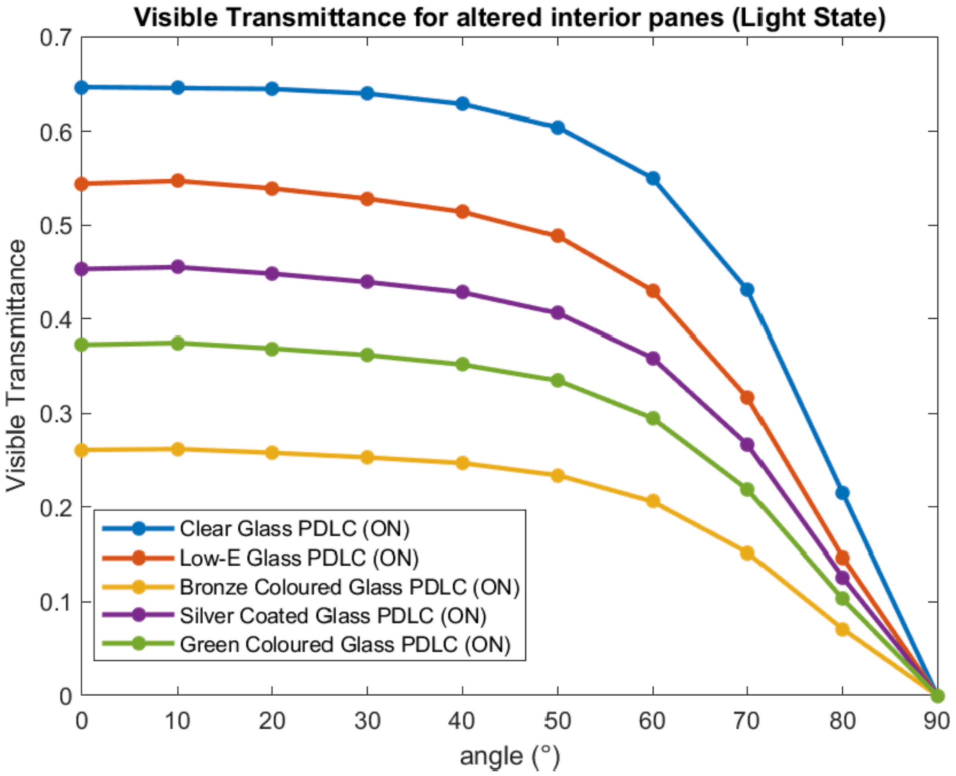

Fig. 7. Relationship between the visible transmittance plot and the incident angle for PDLC glazing in its light ("ON") state with different interior panes.

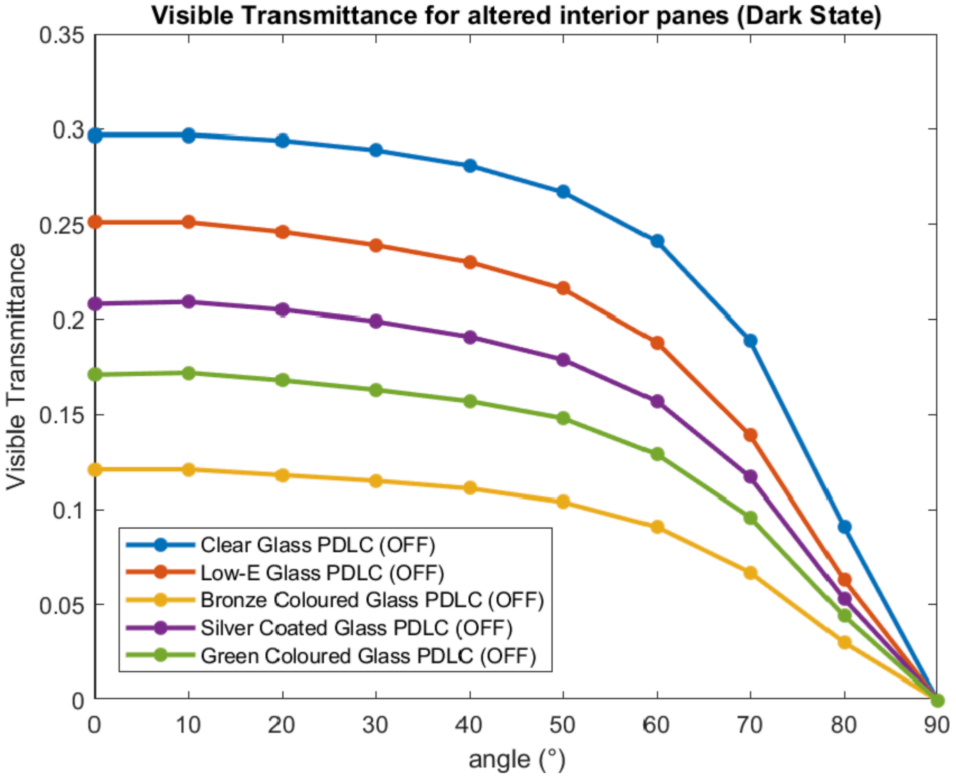

Fig. 8. Relationship between the visible transmittance plot and the incident angle for PDLC glazing in its dark (OFF) state with different interior panes.

optical data are readily available in WINDOW. For PDLC, the optical data for both transparent and translucent states of the PDLC were obtained from a previously conducted experiment (Ghosh and Mallick, 2018b) and imported into Optics, LBNL.

2.2.1. Creating glazing systems in WINDOW

After importing the laminates into WINDOW from the user database, the different glazing systems mentioned earlier were created. All glass used in the glazing systems were from the Guardian Middle East

Table 4
Monthly Maximum and Average Outdoor Temperatures, and average daylight hours in Muscat, Oman.

Month	Maximum Temperature (°C)	Average Temperature (°C)	Average Daylight Hours (hr:min)
January	30.00	21.10	10:53
February	31.00	22.45	11:25
March	38.00	25.03	12:02
April	43.00	29.48	12:45
May	45.50	34.01	13:19
June	47.00	35.07	13:37
July	44.00	33.43	12:30
August	41.90	31.78	12:59
September	42.80	30.91	12:20
October	40.00	29.64	11:40
November	33.00	25.87	11:03
December	30.10	22.47	10:44

Table 5
Energy consumption comparison for different PDLC shading configurations and control types.

Division	Window Switching Energy Usage (kWh)	Cooling Energy (kWh)	Lighting Usage (kWh)	Fans Usage (kWh)	Total Energy (kWh)
Clear (Glare) - Shading turns ON	0	21199.16	5544.21	8795.63	35539.00
Clear (Glare) - Shading turns OFF	179.09	22816.51	4265.44	9263.52	36524.56
Clear (DL) - Shading turns ON	128.91	22256.24	5544.21	9147.54	37076.90
Clear (DL) - Shading turns OFF	347.60	21214.96	3141.91	8663.98	33368.45

Table 6
Total energy consumption of static and switchable glazing systems.

Division	Window Switching Energy Usage (kWh)	Cooling Energy (kWh)	Lighting Usage (kWh)	Fans Usage (kWh)	Total Energy (kWh)
Single Glaze	0	25648.46	6940.29	10385.93	42974.68
Double Glaze (w/ air)	0	23351.25	6940.29	9332.27	39623.81
Double Glaze (w/ argon)	0	23254.40	6940.29	9267.28	39461.97
Electrochromic (DL Control)	94.81	18713.28	5956.90	8084.37	32849.36
Electrochromic (Glare Control)	108.94	18717.38	6185.01	8013.71	33025.04
PDLC (DL Control)	347.60	21214.96	3141.91	8663.98	33368.45
PDLC (Glare Control)	0	21199.16	5544.21	8795.63	35539.00

manufacturer to remain consistent with the location of the simulation. Using 35 mm as the base thickness, all double-glazed systems constructed in WINDOW were made to achieve similar thicknesses (see **section 3**). Static and dynamic double glaze systems were then compared for their energy savings capabilities. During the construction of different glazing systems, low-emissivity (low-e) glass was used due to its lower SHGC properties which are suitable for cooling dominated climates. In WINDOW, low-e glass made by Guardian Middle East has ‘ClimaGuard 70′ in the product name. This glass was applied to the exterior pane to prevent heat gains from outside radiation. The interior pane for PDLC glazing was set as clear float glass and was later changed for other glass types and colours to ascertain the best kind of glass to use to minimise energy use.

2.3. *Simulation parameters*

The simulation was set to a run period of 1 year for the year 2019 with a base temperature of 20 °C, and a time step of 6. This year was chosen to align with the reported IEA data on energy usage and carbon emissions being at all-time high levels. The public holidays in Oman for the year 2019 were added to EnergyPlus under RunPeriodControl:SpecialDays. In this energy simulation, only heating, ventilation, and air-conditioning (HVAC) and lights were considered as energy-consuming elements to simplify the simulation and reduce runtimes (Belzer, 2010). The overhead lighting was set to 10.8 W/m^2 in accordance with ASHRAE Fundamentals standards of 2009. For HVAC, the units used in the building are wall-mounted split system units. They comprise of two components – an indoor air-handling unit known as an evaporator, and an outdoor compressor/condenser. This was defined in EnergyPlus based on the HVAC Template requirements in the Input-Output Reference document. The cooling setpoint was set to 25 °C, which was used in a separate study aimed at constructing a net-zero energy building (Aghniaey and Lawrence, 2018).

The scheduling was customised to suit typical operations in Oman. Typical working hours in Oman are from 8:30 am or 9 am to 5:30 pm or 6 pm. A study about sleep schedules had participants from the United Arab Emirates (Walch et al., 2016). That study found that Emiratis slept at 11:45 pm and woke up at 7:45 am. This finding was assumed to be the same for Omanis due to their geographical proximity and was therefore used for further shaping simulation scheduling. However, with a time step of 6, 45 min past the hour cannot be used as it is not divisible by 6. Therefore, 11:30 pm and 7:30 pm were used instead.

The lighting schedule was adapted from the lighting schedule available in the ‘SingleFamilyHouse_TwoSpeed_CutoutTemperature’ example file that came with the EnergyPlus installation. Oman has Sunday-Thursday as weekdays compared to the EnergyPlus default of Monday-Friday. Therefore, the schedule was detailed using the Schedule:Day:Interval, Schedule:Week:Daily, and Schedule: Year classes (**see** Table 1). A summary of all the main parameters set for the simulations is listed in Table 2**.**

For all simulations, the Output Control:Table:Style was set to HTML with units in kWh. Output:Variable was used to output the direct solar radiation rate per unit area at an hourly rate and Output:Table:Monthly output the average and maximum dry bulb temperature each month (ambient air temperature). Finally, Output:Meter:MeterfileOnly was used to report the monthly electricity usage for heating, cooling, lighting, and fans.

2.3.1. *Switchable glazing*

Switchable glazing can be modelled in EnergyPlus using the Window Shading Control class. To use this class, two separate constructions need to be made: one for the switchable glazing in its transparent state, and one in its translucent/opaque state. All window constructions in FenestrationSurface:Detailed must be set to the state that does not consume energy. In the case of EC windows, the transparent state does not consume energy whereas PDLC windows do not consume energy in their translucent state. The control type is chosen under ‘Shading Control Type’: this study first compared OnIfHighGlare and MeetDaylightIlluminanceSetpoint controls. These two controls were found to offer the best energy savings according to previous studies.

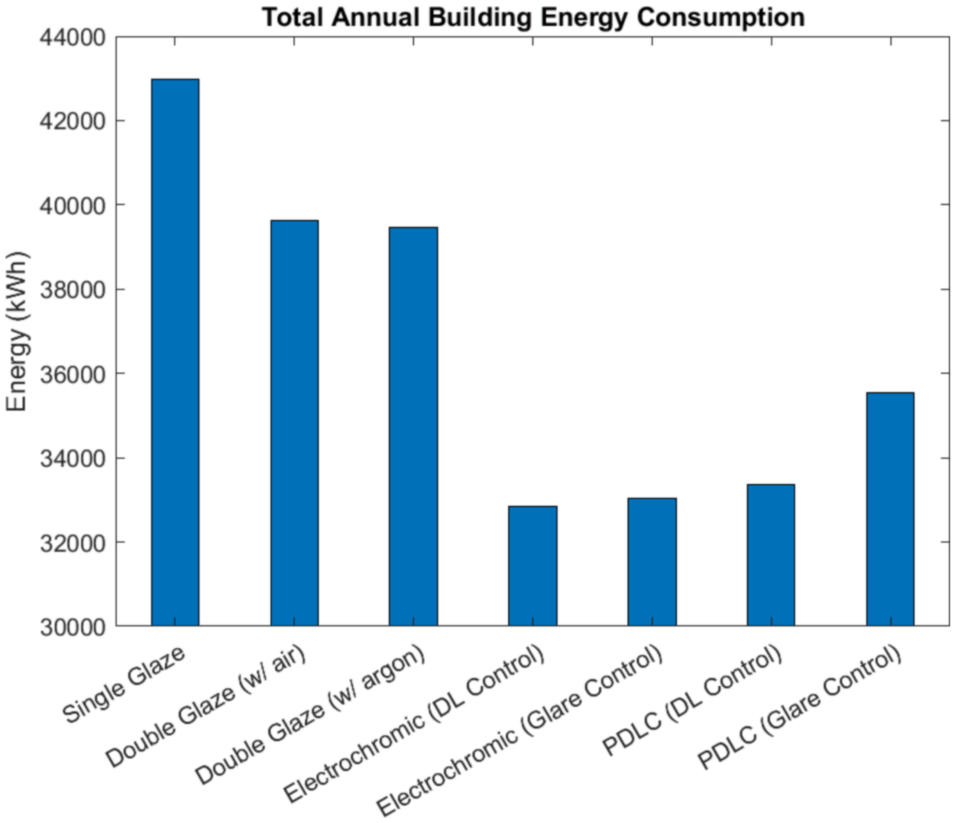

Fig. 9. Column graph of total energy consumption for different glazing systems.

Table 7
Energy savings percentage and equivalent carbon emission for different glazing systems.

Division	Total Energy (kWh)	% Difference (single glaze)	CO_2 emissions ($kgCO_2e$)
Single Glaze	42974.68	–	36791.17
Double Glaze (w/ air)	39623.81	7.80%	33922.45
Double Glaze (w/ argon)	39461.97	8.17%	33783.89
Electrochromic (DL Control)	32849.36	23.56%	28122.75
Electrochromic (Glare Control)	33025.04	23.15%	28273.15
PDLC (DL Control)	33368.45	22.35%	28567.15
PDLC (Glare Control)	35539.00	17.30%	30425.39

Each of the seven zones considered in the building had a Daylighting: Controls and Daylighting:ReferencePoint object. A single reference point for the glare and daylight controls was placed at the centre of each zone and at a height of 0.8 m, which is considered the average table height. Under Daylighting:Controls for all considered zones, the 'Glare Calculation Azimuth Angle of View Direction Clockwise from Zone y-Axis' was set at 20° which was found to be the closest to an average of tested simulated strategies(Dyke et al., 2015). The DGI was set to 20 as is the maximum allowable for a school classroom according to the EnergyPlus Input-Output Reference. This setpoint was chosen due to the current affairs with COVID-19, having children study from home and adults working from home. When the daylight control setting was employed, the illuminance setpoint was set at 500 lx, which was considered the top boundary of supplementary UDI (useful daylight illuminance)(Nabil and Mardaljevic, 2006). This illuminance setpoint was also in line with the EN 12464–1 standard for offices, kitchens and secondary school classrooms. The time that the surface shading is on was output from the Output:Table:Monthly class.

3. Results

3.1. Evaluation of building window using WINDOW

Before conduction energy-based simulations, the optical, angular, temperature, and colour properties of the glazing systems were taken from WINDOW and compared to estimate which glazing would perform better. The first comparison was conducted for the static and switchable glazing systems. Table 3 provides a list of the main optical and thermal properties for the considered glazing. These properties include the *U*-value, SHGC, visible transmittance, and solar transmittance.

The optical properties of the different glazing systems show that the single glaze system allows the most visible light into the room whereas the opaque state of the electrochromic window allows the least amount of light in. Electrochromic windows allow less light and produce less heat gain than PDLC windows, which could lead to electrochromic windows showing better energy performance. While PDLC windows have higher *U*-values than double glazed windows, the translucent state has a lower SHGC value. Combined with the added benefit of the PDLC window states being switchable, PDLC windows could perform better than even double glazed windows as an exterior glass.

The next glazing comparison was conducted for the PDLC double glazing system where the interior glass pane was changed. The glass used for this comparison include clear float, low-e, bronze coloured, green coloured, and silver coated glass. The thermal properties are plotted in Figs. 5 **and** 6. The angular transmission data was plotted in Figs. 7 and 8**.**

With the data output from WINDOW, an analysis on which glazing system and interior pane combination can be made. Bronze coloured glass displays the best thermal properties for reducing cooling load as it has the lowest SHGC value and *U*-value. However, the optical properties of bronze coloured glass would lead to the highest lighting load compared to the other glasses analysed. Green coloured glass and silver

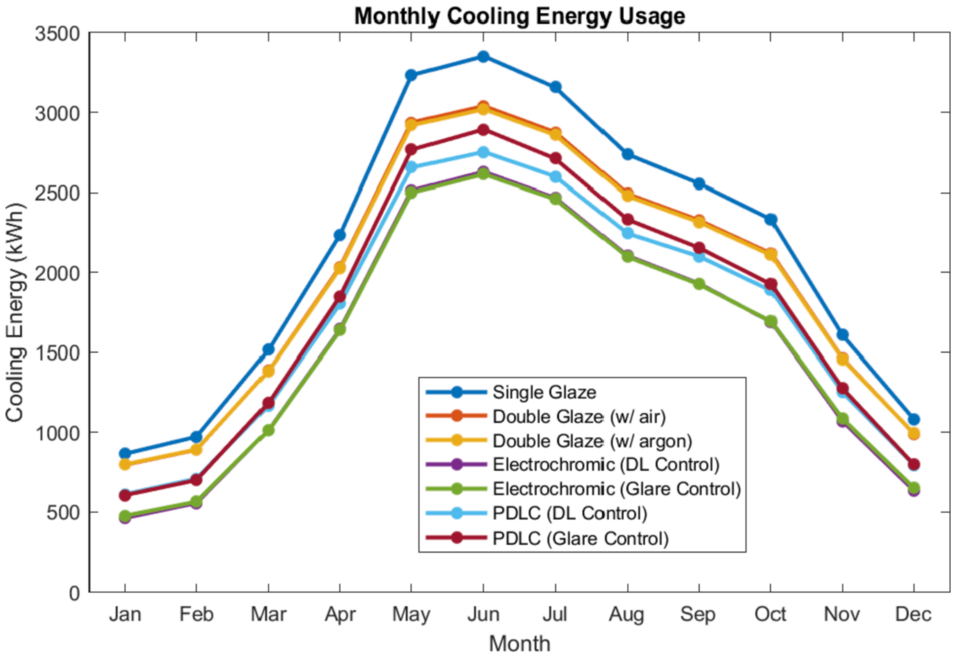

Fig. 10. Monthly cooling electricity consumption of different glazing systems.

Table 8
Total energy consumption breakdown of different PDLC interior pane configurations and control type.

Division	Window Switching Energy Usage (kWh)	Cooling Energy (kWh)	Lighting Usage (kWh)	Fans Usage (kWh)	Total Energy (kWh)
Clear (Glare)	0.00	21199.16	5544.21	8795.63	35539.00
Low-E (Glare)	0.00	20436.55	5886.95	8569.04	34892.54
Bronze Coloured (Glare)	0.00	20132.28	6731.34	8502.21	35365.83
Green Coloured (Glare)	0.00	20070.10	6443.72	8452.70	34966.52
Silver Coated (Glare)	0.00	19885.84	6199.16	8402.99	34487.99
Clear (DL)	347.60	21214.96	3141.91	8663.98	33368.45
Low-E (DL)	298.77	20757.57	3761.76	8542.63	33360.73
Bronze Coloured (DL)	106.40	21408.65	5829.32	8772.07	36116.44
Green Coloured (DL)	185.99	20924.44	4966.01	8560.99	34637.43
Silver Coated (DL)	243.75	20251.46	4367.02	8385.19	33247.42

coated glass both have the same SHGC value and *U*-value but silver coated glass has a higher T_{vis} and T_{sol}, leading to a lower lighting load. Therefore, silver-coated glass predicts to be the most suitable interior pane for double glazed PDLC windows.

3.2. Evaluation of building energy using EnergyPlus

3.2.1. Comparison of static and switchable glazing for Oman climate

The climate conditions for Muscat, Oman were first characterised. Table 4 shows the monthly average and maximum outdoor temperatures obtained from simulations, and the average hours of daylight (Info, 2021). With higher temperatures in the months ranging from May to September (months with a greater than 30 °C average temperature), projected energy usage would be highest in this range.

The first test conducted revolved around the WindowShadingControl class. EC windows consume energy when in their opaque state which is what is required for the shading object to work according to the Input-Output Reference. However, the state that consumes energy for a PDLC window is the transparent state, which does not work as a shading tool. A series of preliminary tests were run with the shading object turning to the translucent state and the shading object turning to the transparent state to confirm the performance characteristics. Both glare and daylighting control (DL) options were tested with both shading configurations to examine which control type produces better energy savings (see Table 5).

Table 5 showed that the optimal PDLC configuration uses the translucent state of the PDLC window as the shade (shading turns OFF) and daylight control (DL) as the shading control type. In contrast, glare control produced better energy savings with the translucent state of the PDLC window as the shade (shading turns ON). Glare control with the transparent state as the shade (shading turns ON) consumed the least amount of electricity on cooling amongst all tested shading configurations. Therefore, the daylighting control using the translucent state as the shade (DL – shading turns OFF), and the glare control using the transparent state as the shade (Glare – shading turns ON) were both employed for further evaluation in section 3.2.2. For window switching energy calculations, the time reported for the shade being used was applied to the calculation and assumed to be the energy-consuming state for the PDLC windows.

The building energy consumption (comprised of cooling, lighting, fans, and window switching usage) was calculated in EnergyPlus for the five glazing systems: single glaze, double glaze (one with air and one with argon in the gap), EC, and PDLC. The exterior glass of the single- and double-glazing systems was set as low-e glass. For switchable windows EC and PDLC, the interior pane was set as clear float glass. The window switching energy (in kWh) was calculated by finding the area of the switching window, multiplying it by the switching power per area and the number of hours the shading was switched on. The switching power per area was taken to be 2.029 W/m^2 (Ghosh and Norton, 2019). The cooling, lighting, and fans usage were taken from the output meter

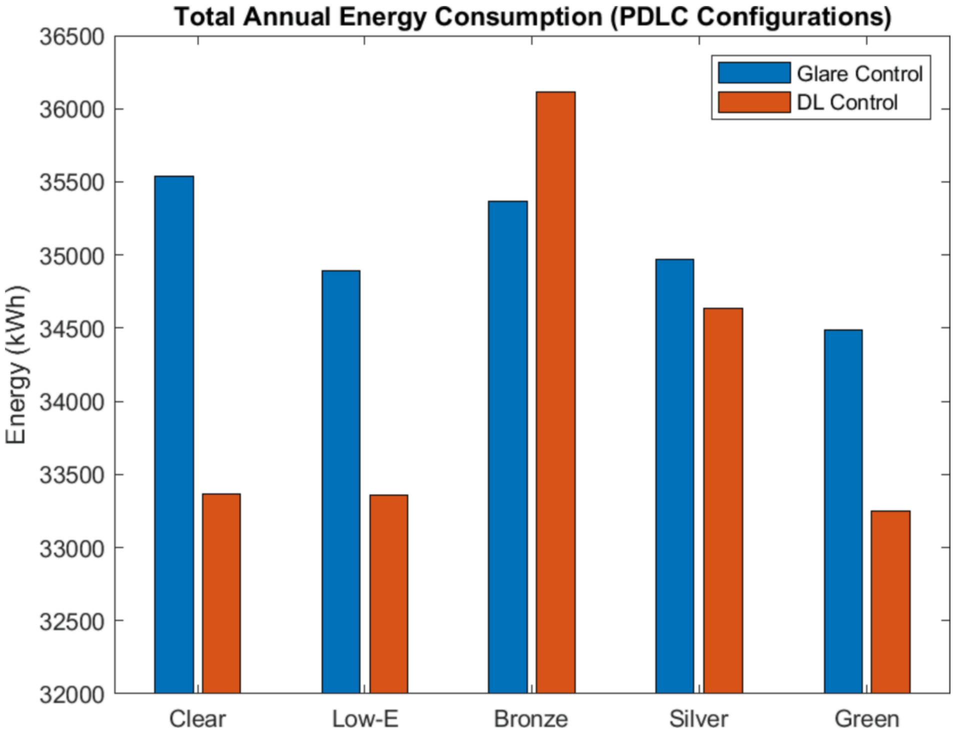

Fig. 11. Column graph of different PDLC interior pane configurations with respect to the employed control type.

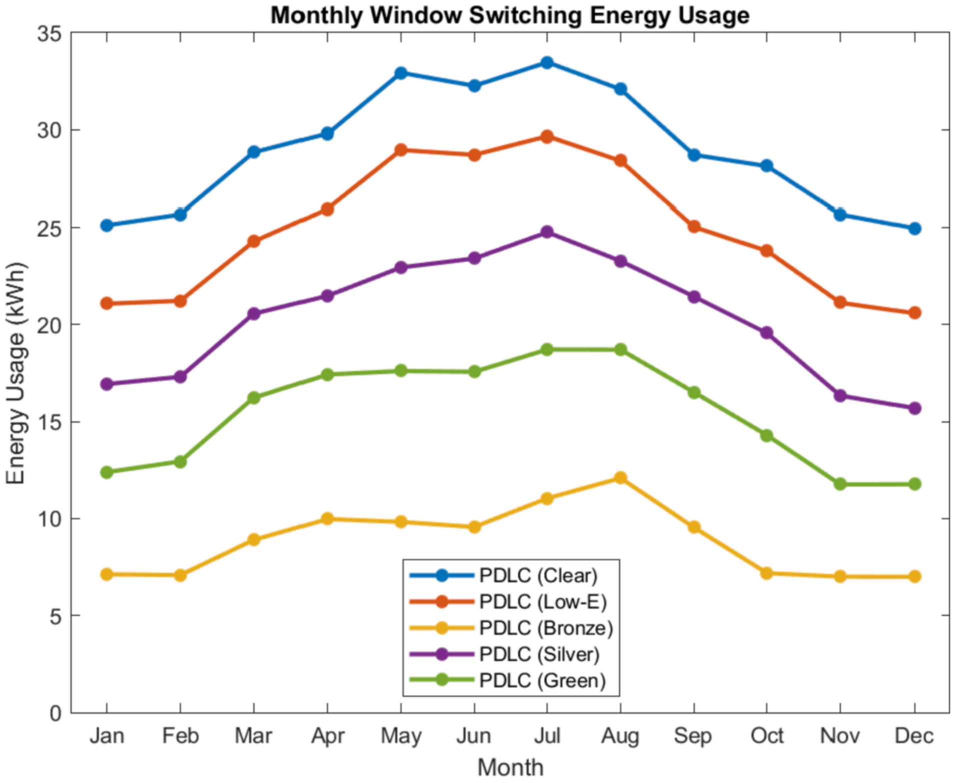

Fig. 12. Monthly window switching energy usage of different PDLC interior pane configurations.

file from the Output:Meter:MeterFileOnly class. These were summed to get the total building energy usage (listed in Table 6 **and plotted in** Fig. 9) and percentage energy savings (listed in Table 7**).**

Table 6 shows that EC and PDLC windows produced the best energy savings with energy savings in all of cooling, lighting, and fan usage. EC windows were predicted to perform the best of all window glazing systems considered based on the optical and thermal properties listed in section 3. To further characterise the energy savings, the equivalent carbon emission savings, and the percent difference in total energy consumption with respect to a single glazed window installation were

Table 9

Percent difference and equivalent carbon dioxide emissions of different PDLC interior pane configurations and control type.

Division	Total Energy (kWh)	% Difference (single glaze)	% Difference (double glaze)	CO_2 emissions ($kgCO_2e$)
Clear (Glare)	35539.00	17.30%	12.13%	30425.39
Low-E (Glare)	34892.54	18.81%	13.49%	29871.95
Bronze Coloured (Glare)	35365.83	17.71%	11.74%	30277.14
Green Coloured (Glare)	34966.52	18.63%	12.91%	29935.28
Silver Coated (Glare)	34487.99	19.75%	14.39%	29525.61
Clear (DL)	33368.45	22.35%	8.44%	28567.15
Low-E (DL)	33360.73	22.37%	10.89%	28560.55
Bronze Coloured (DL)	36116.44	15.96%	11.28%	30919.74
Green Coloured (DL)	34637.43	19.40%	11.57%	29653.54
Silver Coated (DL)	33247.42	22.63%	13.01%	28463.54

calculated (listed in Table 7). The carbon emission equivalent per kilowatt-hour ($kgCO_2e/kWh$) for Oman was taken as 0.856. A monthly cooling energy plot was also created to show the trend of cooling consumption (see Fig. 10).

From Table 7, EC and PDLC windows showed the greatest decrease in energy consumption. The simulation results also showed that daylight illuminance control is optimal in Oman with EC and PDLC reducing energy usage by 23.56% and 22.35% respectively. With the use of switchable windows, the equivalent CO_2 emissions were reduced by at least 8,000 $kgCO_2e$. Fig. 10 showed that months with higher average temperatures saw greater cooling energy usage. However, the monthly cooling consumption between control types of the same glazing hardly differed. The difference in total energy consumption was mainly caused by the amount of lighting energy saved by using daylight control.

3.2.2. *Optimising interior pane of PDLC glazing for Oman climate*

Energy simulations were conducted for different interior panes in the PDLC glazing system. As described in section 3.2.1, the two control schemes employed are as follows: glare control using the transparent state used as the shade, and daylight setpoint control with the translucent state as the shade. These were tested to find which combination of a control type and interior pane would yield the best energy savings. The energy consumption is listed in Table 8 and a column graph was drawn to compare the annual energy consumption (see Fig. 11). Additionally, the monthly switching energy for all configurations was plotted in order to compare and analyse the effect of the interior pane on switching energy usage (see Fig. 12).

The tables and figures above show that daylight control performs better for all PDLC interior pane configurations except bronze-coloured glass. This glazing system had the largest lighting usage with both control schemes due to its low visible transmittance. The switching energy usage for both coloured glass PDLC glazing systems was the smallest due to both systems having very low visible transmittance even in the transparent state. Since the control system required the illuminance set point to be reached, the cooling energy usage was larger than that shown using glare control. Furthermore, the cooling energy usage for bronze coloured glass was even greater than clear glass, which had the highest SHGC and *U*-value.

In contrast, all non-coloured glass had significantly decreased energy consumption with daylight control as opposed to glare control. This was due to a decrease in lighting usage (cooling and fan energy usage were similar for both glare and daylight control). Therefore, daylight control was found to be more effective in Oman. Since silver coated glass had the lowest SHGC value, *U*-value, and the highest solar reflectance, the PDLC glazing system with silver coated glass showed the best energy savings. Compared to a clear float glass PDLC glazing system, the increase in energy savings displayed by the silver-coated glass is minimal; saving 121.03 kWh and 103.62 $kgCO_2e$ with a percentage difference of 0.28%.

All PDLC configurations showed greater switching energy usage with daylight control in the summer months compared to the other months due to more hours of daylight. With glare control, the PDLC glazing system remained in the translucent state and the shade (transparent state) was not utilised. The percent difference in energy savings with respect to the single glass configuration and the equivalent carbon emissions were listed in Table 9.

4. Conclusion

This study aimed to evaluate the impact of electrically actuated smart switchable glazing systems particularly PDLC and EC types on the energy usage of a residential building in Oman. Results were compared with single, air filled double glazing and argon filled double glazing. Later, PDLC glazing was modified by clear float, low-e, silver coated, bronze coloured, and green coloured glasses and further building energy analysis was performed. The optical and thermal properties of these different switchable and static window glazing systems were analysed using WINDOW (from LBNL).

Electrochromic windows showed the best optical and thermal properties, having the lowest SHGC, *U*-value, T_{vis}, and T_{sol}. PDLC windows have better optical properties but inferior thermal properties than the considered static glazing systems. Due to the nature of energy consumption for PDLC window operation, both glare and daylight illuminance control types were tested with the transparent and translucent states as the shading construction. This was done to aid in concluding which control type is optimal for Oman's climate. The result of the building energy simulations showed both switchable windows outperforming the static glazing systems. Electrochromic and PDLC windows caused reductions in cooling, lighting, and fan usage with a percentage difference relative to a single glazed window of 23.56% and 22.35% respectively. Furthermore, CO_2 emissions were reduced by more than 8,000 $kgCO_2e$, making both EC and PDLC windows lucrative for both energy and emissions savings.

The optimal interior pane of the PDLC double glazing was found by testing five different types of glass: clear float, low-e, silver coated, bronze coloured, and green coloured. Their thermal and optical properties were collected from WINDOW and analysed. PDLC with silver coated glass displayed the best optical properties along with good thermal properties. Silver coated was therefore predicted to display the largest reduction in energy consumption. The simulation was conducted with both combinations of a control type and shading object. It was found that silver coated glass performed the best out of all the interior glass choices. However, the decrease in energy consumption compared to clear float glass was minimal (121.03 kWh, 103.62 $kgCO_2e$, and an equivalent 0.28% reduction in energy consumed).

Declaration of Competing Interest

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

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