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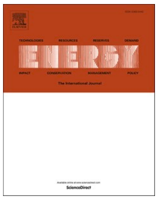

Energy assessment of advanced and switchable windows for less energy-hungry buildings in the UK

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ABSTRACT

Globally, greenhouse gas emissions from the operational phase of buildings are significantly contributing towards climate change. Global and national efforts, through the Sustainable Development Goals and the UK's 2050 targets, aim to reduce these emissions with net zero energy buildings (NZEBs). A building's glazing plays a significant role in overall building energy consumption due to their traditionally 'leaky' nature. This study utilises experimental data from test cells and the International Glazing Database to evaluate the performance of advanced and smart/switchable windows on an existing low energy building (LEB) situated in north Wales, UK, as a step towards making the modelled building a NZEB. A number of glazing constructions were considered in this work; advanced window – vacuum, aerogel, vacuum-aerogel and smart window – PDLC, PDLC-aerogel and PDLC-vacuum, in their fixed and switching states. Results revealed that PDLC-vacuum offered the greatest reduction in building energy, yielding a theoretical *U-value* of 0.810–0.831 W/m^{2}K and a *G-value* of 0.257–0.455. Despite its successes, it was notably susceptible to window orientation and window-to-wall ratio. Vacuum and aerogel glazing both offered similar energy savings, with the latter prone to overheating, stressing cooling loads. These advanced windows offered differing daylighting potential with vacuum able to meet 78% of useful daylight illuminance compared to aerogel's 60%. Given the prioritisation trilemma between heating, lighting and cooling needs of a building, PDLC-vacuum presents the best step towards a NZEB. As such, further efforts should concentrate on the development of a PDLC-vacuum window, maintaining smart window functionality and achieving low *U-value* for cold climates.

1. Introduction

The concern of anthropogenic climate change has recently led to global efforts to address a reduction in the energy needs of all. Globally, the building sector accounts for 40% of total energy demand, contributing towards 30% of greenhouse gas emission [1]. In response, the 2015 Paris Climate Agreement sets out to limit average temperature rise to <1.5 °C by 2050 [2]. Similarly, the United Nations Sustainable Development Goals aim to tackle climate change and strive for environmental protection [3]. Notably, SDG-11 looks to develop sustainable cities and communities, whilst SDG-7 aims to double the rate in improvement of energy efficiency by 2030 [4,5]. Recently efforts have targeted the use of energy through the operational phase of buildings with policymaking [6]. The UK Government has set out ambitious legislation for an 80% carbon reduction by 2050, aiming for a 68% reduction by the end of this decade [7]. This is seen as especially challenging for the Government [7], and is further exacerbated as 46% of homes were built between 1930-82 [8]. And of the 28 million households, 86% use natural gas boilers [9]. Improvements in building energy efficiency, particularly given the cold climate of the UK, are clearly critical to address these carbon reduction commitments. This has led to terms such as Nearly Zero Energy Building (NZEB) and Low Energy Building (LEBs).

Given the motivation for LEBs and NZEBs, initially, it is important to consider a building's envelope; comprising of windows, doors, walls and foundations [10], of which windows are seen as the weakest component, responsible for up to 60% of building energy loss [11]. Fortunately, they are an easy component to retrofit, offering significant improvements. The applicability of windows is dictated by its characteristics; *U-value*, the heat transfer coefficient, is regarded a measure of the glazing's resistance to heat loss. Whilst solar heat gain coefficient (SGHC/*G-value*) dictates heat gain into the space. Both coefficients determine the thermal behaviour of the glazing, and as such have consequential impacts on the heating, ventilation and cooling (HVAC) demands of conditioned zones. Visible transmission (T_{vis}) is also a defining factor of windows.

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Nomenclature

U-value	Thermal transmittance (W/m^{2}K)
T_{vis}	Visible transmittance (−)

List of Abbreviations

LEB	Low Energy Building
BEM	Building Energy Model
LPD	Lighting Power Density
WWR	Window-to-Wall Ratio
HVAC	Heating Ventilation and Cooling
UDI	Useful Daylight Illuminance
PDLC	Polymer Dispersed Liquid Crystal
SGHC	Solar Heat Gain Coefficient
PBP	Payback Period

Windows primarily allow occupants to connect with the outside world, and daylighting, dictated by the visible transmittance of the window, has profound impacts on occupants. Illuminance of the space is useful to reduce artificial lighting needs, but excessive lighting or glare could be problematic. Daylighting for occupants also alters their perception of thermal comfort and added health benefits [12,13]. Fig. 1 illustrates the processes acting on a traditional double-glazed window; the resultant impact of heat gains, losses and lighting needs due to window selection is significant as these demands dominate a building's energy usage, hence is the primary assessment of this work.

Different climatic regions demand different functionality of windows; for the colder climate of the UK, it is desired to retain heat inside the property to provide thermal comfort for the occupants. High *U-values* are detrimental to the building's envelope meaning additional heating needs for the occupant, at financial and environmental cost. However, heat gains through the window are beneficial to warm the space, but overheating ought to be avoided. Daylighting utilisation is similar, offering daylight whilst maintaining visual comfort for the occupant's visual comfort [14]. 87.5% of UK households have double glazing windows fitted [15], and in as recent as 2013, the UK Building Regulations Part L, only specified a maximum of 2.00 W/m^{2}K [16]. This dramatically falls short of the lower *U-values* needed for LEBs. The need for retrofit and window improvement to achieve the carbon reduction targets, given the carbon intensive natural gas dominated heating network, cannot be further stated.

In recent times much research attention has been given towards the development of improved windows and their simulation [2,17–19]. In particular, the response of different windows on the heating, cooling and lighting demands of the building [20,21]. Windows have previously been classified on their applicability to their operating climate or ability to control heat loss [22], recently Ghosh proposed classification of windows for low-energy buildings by their transmission properties and working principle [23]. Categorised into advanced and smart/switchable window categories, windows of varying technology readiness level (TRL) are arranged. Within the latter, further division can separate windows by electrically and non-electrically actuation.

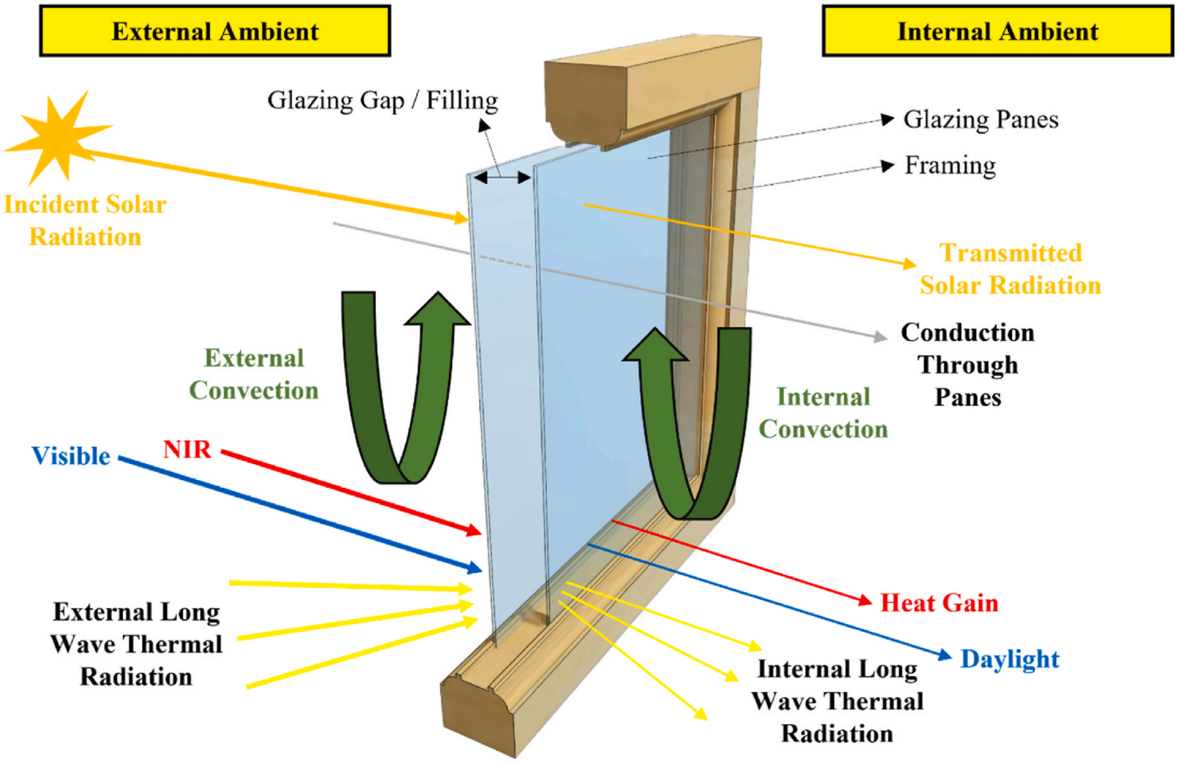

Fig. 1. Schematic of processes acting on a double-glazing unit.

Smart windows are dynamic by nature, modifying their properties dependant on the surrounding environment or electrical input to regulate the indoor environment [22,24]. Influence from the surrounding environment on smart windows can be in the form of temperature - thermochromic [25] and thermotropic [26], light - photochromic [27], or gas - gasochromic [28]. Conversely electric actuation can include polymer-dispersed liquid crystal (PDLC) which requires the presence of an AC current for actuation to turn transparent [29]. The operation of a PDLC structure is detailed in Fig. 2. Other examples include electrochromic [24,30,31] and suspended particle devices [32]. The 'smart' nature of these glazings is their ability to adjust their light transmission without the aid of additional shading devices, to optimise user comfort [32].

Advanced window refers to windows of improved energy efficiency

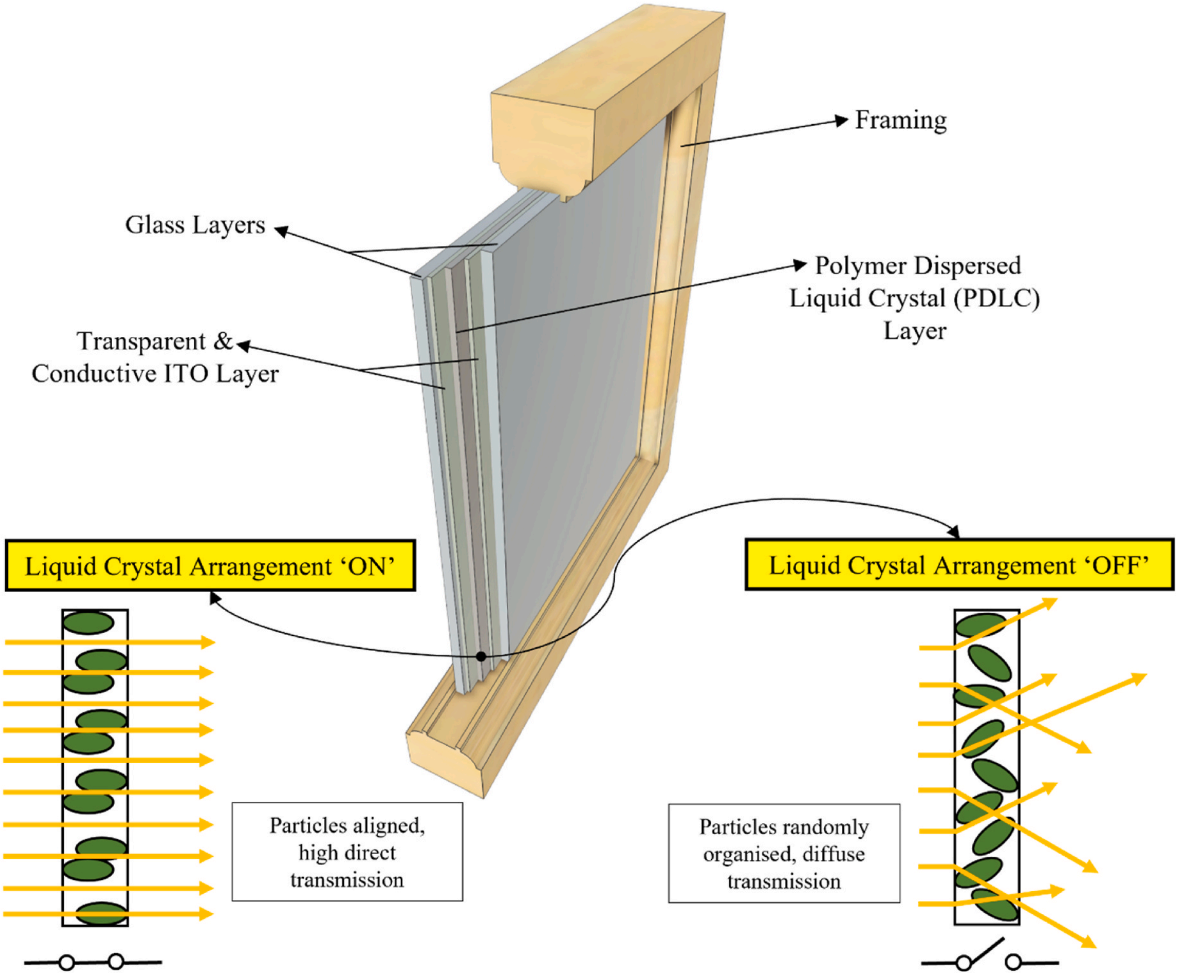

Fig. 2. Schematic of PDLC glazing operation in its 'on' and 'off' states.

compared to traditional double- and triple-glazed windows [23]. These glazings by comparison are static, of passive operation, and include aerogel [33], vacuum [34] and photovoltaic [35]. This category also extends to more novel research foci; water [36], transparent wood [37], and prismatic film [38].

Aerogel's properties make it extremely attractive for glazing applications; a lower thermal conductivity than air, non-toxic, lowly flammable and low-density nature advocate its suitability for low heat loss buildings [23]. Granular aerogel has been considered for both the hot and cold climate, noting its significance in the warmer climate, with *U*-values of ranging 0.25–1.38 W/m^2K [39]. Ihara et al. concludes the possibility of a combined aerogel-triple glazing system may achieve improved performance for the cold climate [39].

Similarly vacuum glazing, two vacuum separated glass panes, offers high thermal insulation whilst maintaining high transmittance as the vacuum layer reduces conductive and convective heat flow [11]. Able to yield *U-values* of $<1W/m^2K$, work by Fang and Arya sought to further improve on this by reducing support material required to separate the panes in the evacuated region with tempered glass [40]. Reduction in conductive heat transfer with tempered glass led to a 47% improvement in thermal transmittance (0.3 $W/m^{-2}K^{-1}$) for double glazed units compared to annealed ones [40].

Work with smart window, specifically with PDLC has been considered for the hot climate [20,29]. Result from Hemaida et al. suggest that there could be a role in PDLC reducing heating loads in cold climates with a *G-value* of 0.68 and 0.63 for transparent and translucent states [41]. The PDLC constructions however maintained *U-values* of 2.79 W/m^2K and 2.44 W/m^2K, respectively [41].

Previous articles have considered simulation work with a variety of advanced and smart windows, often in comparison to a baseline double glazing; notably in Oman [20], Korea [2,42], Italy [27] and the UK [10]. Iluyemi et al.'s study revealed smart electronic windows yielded a 23.5% reduction in overall building energy compared to single glazing, for the hot climate of Oman [20]. Conversely Mohammad and Ghosh's assessment of aerogels yielded an overall 15.5% reduction in heating demand for simulation in the UK [10].

To date, limited work has explored simulation with an integrated vacuum-PDLC construction. Therefore, the aim of this study is to consider a comparison between advanced glazing, existing smart windows and novel, theoretical, smart windows with aerogel and vacuum layers. The novelty of this work is in its usage of data from previously conducted test cells to generate theoretical constructions for comparison between existing advanced and smart windows. Specifically, this work focuses on comparing the novel constructions in the low-energy climate of the UK; modelled on an existing LEB, attempting to drive the modelled building towards a NZEB. This work will examine the HVAC and lighting implications of each construction on the modelled building, considering the thermal response of the property throughout a test year. **Section 2** of this paper will outline the methodology of this work, culminating in simulation parameters. Results will be detailed in **Section 3**, detailing building energy results, investigation of the building orientation and window-to-wall ratio. Daylighting analysis will visually illustrate and quantify the window's seasonal impact on daylighting given a Useful Daylight Illuminance index [43]. Costing analysis will consider the lifetime savings property owners could receive with the tested glazing types. **Section 4** will collate the main findings of this

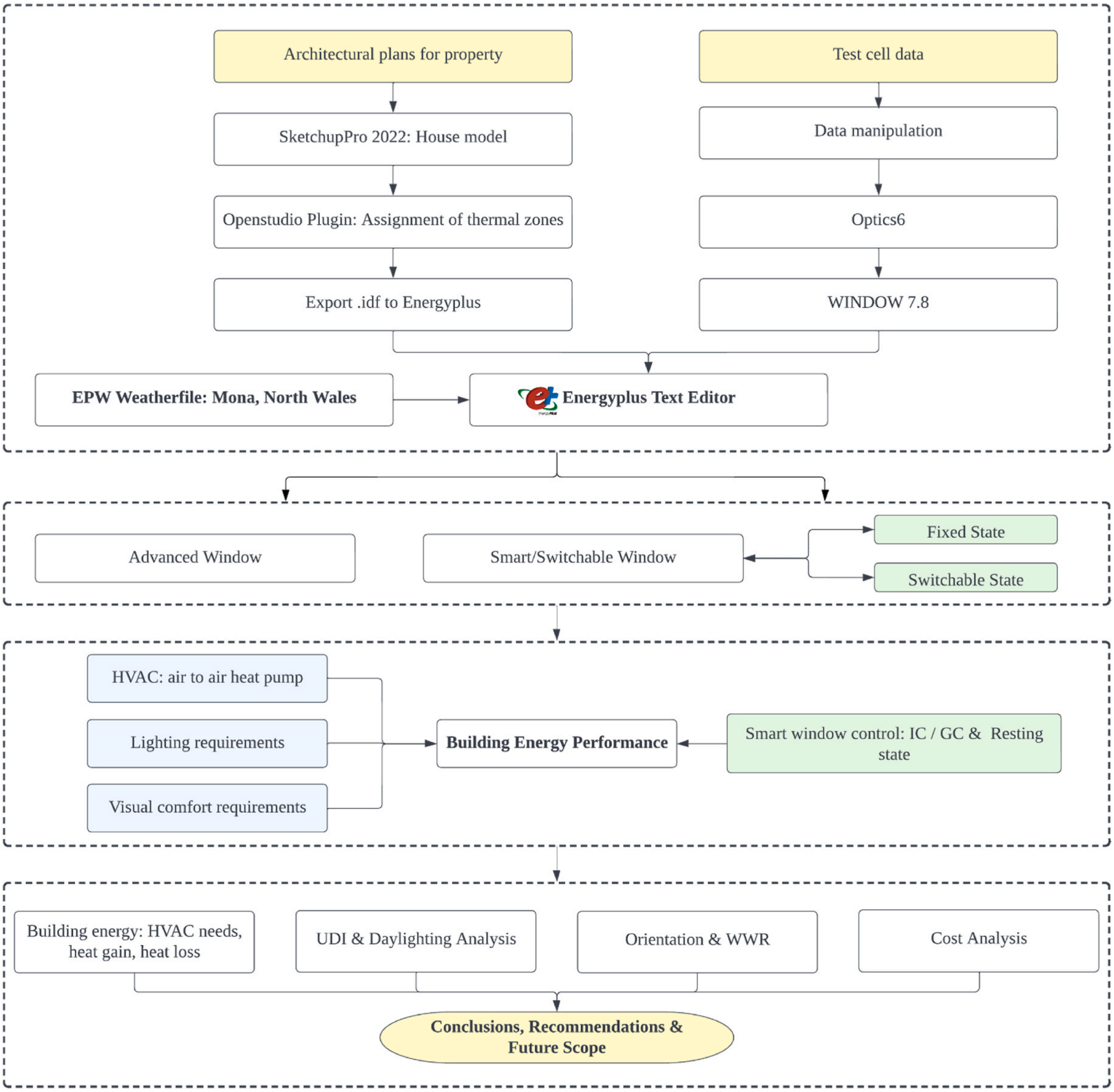

Fig. 3. Methodological approach of this work.

work, pointing to areas of future scope.

2. Methodology

Variance with total building energy demand due to different glazing is the primary assessment of this work. The following simulation aims to develop an understanding of the potential energy savings from efficient windows on a prototypical, low energy building, in the cold climate of the United Kingdom. In addition to this, sensitivity analysis is performed, as well as illuminance analysis, to understand the impact of changing glazing internally. A brief costings analysis is included to further justify glazing selection. Fig. 3 outlines a detailed flow chart of this work, detailing the approach of initial data processing and simulation, leading to conclusions for each investigated aspect. As per Fig. 3, several key programs are required to facilitate each of these analyses, and their usage can be summarised as follows:

- **Optics6** is used to take the optical data from test cells and process it as layers.
- **WINDOW** takes the exported **Optics6** layers to generate constructions (of multiple layers).
- EnergyPlus is used to develop a BEM (Building Energy Model), importing differing window constructions generated in **WINDOW.** Multiple simulations are run for each window category: smart/switchable and advanced. Subsequent analysis in **EnergyPlus** is performed by varying simulation parameters via the Class List.
- **Autodesk's Revit**, with its **Insights Energy Analysis** plugin, is used to construct an identical building model as EnergyPlus and runs daylighting analysis for a user-specific date and time.

Further aspects of this flow chart are explained throughout Section 2.

2.1. *Prototypical building modelling*

Initially a Building Energy Model (BEM) is developed to evaluate energy savings following changes to the building's transparent fenestrations. This work models these implications on an existing structure conforming to UK building regulations; a three-storey guesthouse, 'Plas Gwylan'. Built in 2018, the domestic property presents a large household for up to 20 residents, located in North Wales, Rhosneigr, Anglesey, United Kingdom (53°13′40.0"N 4°31′08.4"W). The building comprises of

Fig. 4. The dimensioned Sketchup model of Plas Gwylan, Anglesey.

Table 1
Surface U-values.

Construction[a]	*U-value* (W/mK)
Internal Wall	0.326
External Wall	0.152
Ground Floor	0.121
Interior Floor/Ceiling	0.293
Roof	0.150

[a] Reported using the EnvelopeSummary in Output:Table: SummaryReports class.

a total floor area of 470 m^2, 10 bedrooms, a kitchen-diner facility, 8 bathrooms, a large lounge, and an integrated garage. Plas Gwylan also benefits from a low average wall *U-value* of 0.20 W/m^2K and a heat pump for space heating.

For the BEM Plas Gwylan was drawn in Sketchup Pro 2022. EnergyPlus was selected as the simulation software for the modelling due to its significance in recent works [10,20,42,44]. Translating the 3D Sketchup model to EnergyPlus required the use of OpenStudio's plugin to integrate EnergyPlus functionality. Its' proprietary inspector allowed the assignment of thermal zones and surfaces. This enabled import and export of.idf files, EnergyPlus files, through the development stages. Due to the extensive dimensions of the property, a simplified approach was devised, modelling the building on space-use to determine thermal zones. 13 thermal zones were modelled, the first and second floors were simplified into large, shared spaces, which include the bedrooms, lounges and a walkway. The ground floor spaces differ, including the garage, utility, lounge, atrium and kitchen spaces. Assignment of the internal-external wall and floor-ceiling relations was then performed with the OpenStudio plugin, through the 'surface matching' tool, Fig. 4.

Dimensions of fenestrations were modelled as per the building's architectural drawings. Flat roofs were adopted in the simplified model, and skylight windows were placed according to their projected view on the floor space. In EnergyPlus' IDF editor, wall constructs were defined as per specifications provided by Kingspan GB and Standard Assessment Procedure calculations provided by the property owner. Performance of materials was sourced from each manufacturer or the Integrated Environmental Solutions reference database [45]. Table 1 illustrates the surface properties modelled in EnergyPlus.

2.2. *Glazing systems: WINDOW & Optics6*

Initially single, double (air-filled), vacuum, aerogel, and switchable PDLC glazing was considered. For the latter three, data from previously conducted experiments was utilised [46]. This data included transmission and reflection values for test samples across a wavelength range of 300 nm–2500nm. Optics6 was used for processing this data to develop spectral properties required for WINDOW 7.8. Optics6 is a Lawrence Berkely National Laboratory (LBNL) software designed to work with optical data and the International Glazing Database (IDGB), allowing results to be exported to WINDOW [47]. The proprietary text files required for import of this optical data were subsequently produced. Given Ghosh and Mallick's study [46], importing sample data as laminates was deemed most suitable. Data for each sample was processed with **Equation (1)**, to determine its transmittance, reflectance, and average emissivity, required for the text file input. Formatting of each text file was performed as per the exemplar files on the LBNL IDGB Data Format webpage [48].

$$A + T + R = 1 \text{ (Where } A = E) \tag{1}$$

A *is absorptance*, T *is transmittance*, R *is reflectance and* E *is emissivity*

Each sample's text file was imported into Optics6 and saved to the User Database. These laminates were then imported into the Glass Library of WINDOW. Development of glazing systems followed, creating new constructions in the Glazing System Library. Switchable PDLC constructions were developed for 'on', translucent, and 'off', diffuse, states. PDLC constructions mimic with that of another study [20] using the same data. The vacuum sample was sized to 6.2 mm in thickness; the thickness of Pilkington's Spacia vacuum windows [49]. WINDOW's Glazing System Library contained sufficient components to assemble a Pilkington Spacia window as well, providing comparison to the study's data. To provide direct comparison, the aerogel sample was sized to align with the construction of the vacuum glazing. Generic single and double glazing constructions in WINDOW were selected to provide baseline comparisons.

The recent proposal of integrated PDLC-vacuum glazing [11] is also

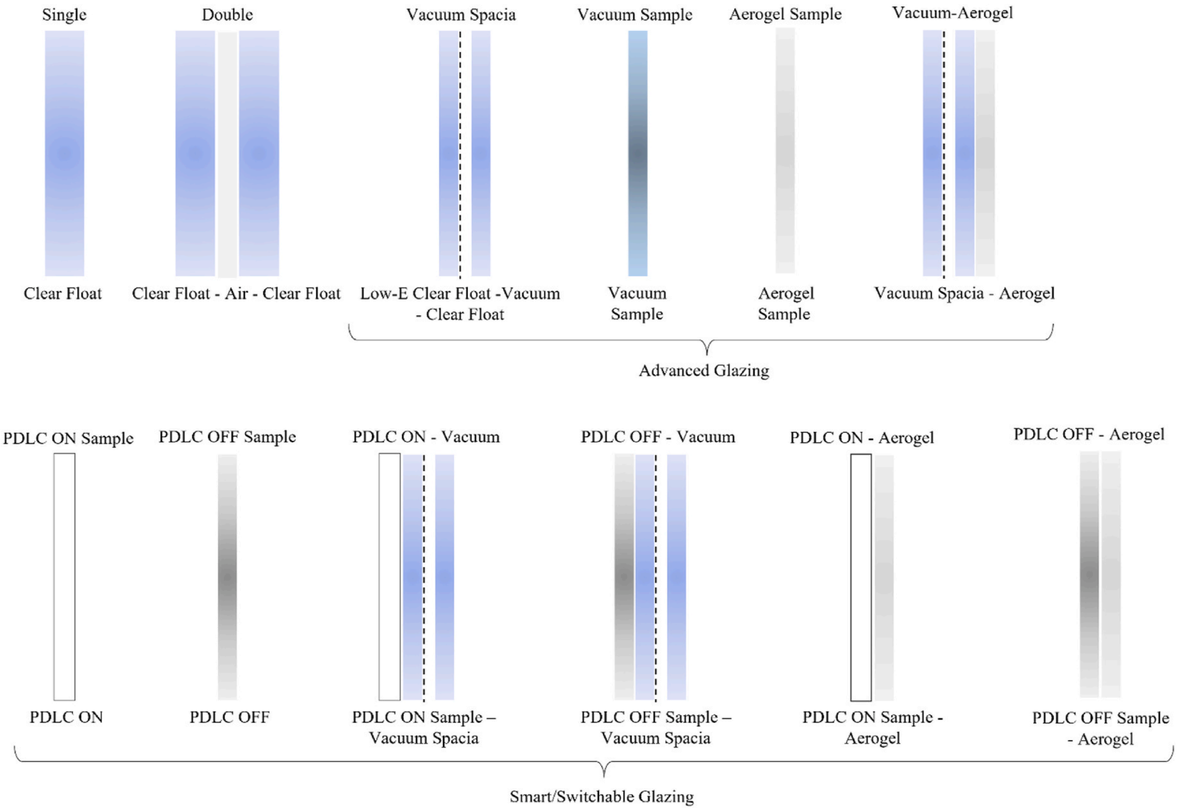

Fig. 5. Cross sections of glazing systems modelled.

Table 2

Glazing system properties from WINDOW.

Glazing	*U-value* (W/m^{2}K)	SHGC/*G-value*	T$_{vis}$
Single	5.818	0.818	0.884
Double Air Filled	2.703	0.704	0.786
Aerogel	0.699	0.552	0.376
Vacuum Spacia	1.037	0.692	0.771
Vacuum Sample	0.978	0.703	0.814
Vacuum-Aerogel	0.457	0.476	0.328
PDLC ON	2.409	0.557	0.640
PDLC OFF	2.573	0.360	0.295
PDLC-aerogel ON	0.587	0.364	0.283
PDLC-aerogel OFF	0.599	0.209	0.131
PDLC-vacuum ON	0.810	0.455	0.569
PDLC-vacuum OFF	0.831	0.257	0.261

Table 3

Daily schedule of occupant activity to determine fractional lighting usage.

Field	Units	Obj1	Obj2
Name		Lights Weekday	Lights Weekend
Schedule Type Limits Name		Fraction	Fraction
Interpolate to Timestep		No	No
Time 1		06:30	06:30
Value Until Time 1	Units	0	0
Time 2		09:00	23:00
Value Until Time 2	Units	0.2	0.05
Time 3		17:00	24:00
Value Until Time 3	Units	1	0
Time 4		23:00	
Value Until Time 4	Units	0.2	
Time 5		24:00	
Value Until Time 5	Units	0	

considered, as well as an experimental PDLC-aerogel integrated construction. A hybrid aerogel-vacuum triple-glazing construction is proposed to achieve even lower *U-values*, addressing the need for improved *U-value* without excessive compromise on transmission. Fig. 5 illustrates the cross sections of all glazing systems developed in WINDOW used in this simulation.

Results of each glazing construction from WINDOW were inputted into EnergyPlus, Table 2 shows these results used in the simulation.

2.3. Energy simulation parameters

Location parameters were inputted to align with the correct orientation of Plas Gwylan, adjusting the North axis by 220° Google Earth Pro was used to determine this. A Conduction Transfer Function (CTF) was selected as the Heat Balance Algorithm, with a simulation timestep of 6. A weather file was provided by OneBuilding.org with data for Typical Meteorological Years (TMYs) in the EnergyPlus format, EPW [50]. The TMY weather file for Mona, Anglesey, was selected due to its geographical proximity to Rhosneigr, which was unavailable. The sizing period was selected as WeatherFileDays class, for the year-long period. A RunPeriod of 2022 was selected, aligning with the emergence of the COVID-19 pandemic where holidaymakers faced no restrictions. Public holidays for 2022 were inputted too.

In this simulation energy consumption is simplified; interior lighting, heating and cooling needs (referred to as HVAC requirement) are only considered. This simplified approach is recognised as a limitation of this work. Whilst EnergyPlus has functionality to support more detailed models e.g., temperature effects due to cooking and electrical devices, this work is focused on the relative reduction of differing window constructions as opposed to a complete representation of Plas Gwylan's energy balance.

As such, interior lighting, heating and cooling energy demands were defined and scheduled accordingly. Availability of lighting was scheduled as per another study [20], adapting the lighting schedule from SingleFamilyHouse_HP_Slab example file. Lighting demand is modelled

Table 4
LPD per ASHRAE guidance applied to Plas Gwylan.

ASHRAE Space	Space in house	LPD (W/m^2)
Atrium	Atrium	4.2
Corridor	2nd Floor Walkway	4.0
Storage Room	Utility	3.7
Dining Area	Kitchen-Diner, Lounge	6.6
Classroom	Bedroom^2	6.9
Emergency Vehicle Garage	Garage	5.1

as a fractional schedule and sleeping hours are required to complete this. For the United Kingdom sleeping periods are averaged to 23:00–06:30 [51,52], with working hours, from 09:00–17:00, Table 3.

Lighting consumption was defined in terms of Lighting Power Density (W/m^2), utilising values from comparable spaces defined in ASHRAE Guidelines for green buildings [53]. Table 4 defines overhead lighting assumptions in the context of these guidelines applied to each space.

Plas Gwylan's primary space heating is provided by an air-source heat pump (ASHP).[1] A Variable Refrigerant Flow (VRF) air-to-air heat pump is modelled following the EnergyPlus Input-Output documentation template with a CoP of 3.4. An availability schedule was set, offering 24-h availability, with continual Dual Thermostat setpoint control; heating and cooling setpoints of 20 °C and 26 °C respectively [42]. All thermal zones were conditioned, with the exclusion of the garage. Sizing of the system was performed under the SimulationControl class, performing HVAC sizing for the specified sizing period. A master thermostat was required, this was located in the ground-floor kitchen. Control type was set to MasterThermostatPriority, prioritising this space due to its large, communal area, in the property.

Under Daylighting:Controls class, Reference Points were placed as per the EnergyPlus Input-Output documentation, at a standard height of 0.8 m [54]. A setpoint of 500 lux was employed: the recommended illuminance for generic office work as per the forementioned documentation. Similarly, a Discomfort Glare Index (DGI) was set at 20, at an azimuth of 20° [54] aligning with the increase in remote working [55]. For switchable constructions, where light transmission is variable, achieving illuminance setpoints is possible through shading control. With the WindowShadingControl class, window constructions can be manipulated according to these setpoints. Group control was assigned for spaces with multiple switchable fenestrations.

The resting state of the switchable window can be manipulated, and savings compared. It is important to consider the 'switching' energy consumption of the glazing. Calculation of the shading 'on' period can be calculated from the WindowReportMonthly output. Shading control type is considered to determine the lowest building energy consumption; MeetDaylightIlluminanceSetpoint and OnIfHighGlare: illuminance and glare control respectively.

2.4. Illuminance simulation

Illuminance analysis with Autodesk's Revit is utilised to contextualise the Useful Daylight Illuminance (UDI) of the first floor of Plas Gwylan (Ecotect 2011 is no longer supported, and now integrated into Revit). The property was modelled in Revit, with its location and orientation assigned. Reflectivity of opaque materials for illuminance analysis was assigned, assuming white paint on internal walls. Traditionally UDI is used a 'holistic' tool over an extended period [43], Revit's Insights Lighting Analysis plugin is limited to static UDI reporting. Hence this study only considers UDI for the summer and winter solstices at midday. Each glazing's visible transmission was implemented by modifying its colour appearance RGB value. This was guided by the Autodesk documentation [56], and for laminated constructions a 'single' layer was considered. UDI thresholds were set according to a useful range of 100–2000lx [43] whilst Revit's analysis reported percentage of floor area, below, within and exceeding this threshold. Heat maps of the floor plan are reported for 0–500lx on the summer solstice, where 500lx is the minimum work plane illuminance that can be met by daylight alone [43], this narrower range was decided to present more distinguishable results given the expected poor illuminance of PDLC 'off' states and aerogel constructions; to serve as a 'baseline' comparison between constructions. This offers an alternative measure of illuminance, visualising artificial lighting requirement compared to the UDI.

Table 5
Windows replaced in each scenario.

	Zones Targeted	Total surface area of replaced windows (m^2)
Targeted Heating Loads	7,11,13	18.28
Targeted Cooling Loads	6,8,13	31.10
Targeted Lighting Loads	6,7,8	29.16

2.5. Costing analysis

Given the LEB nature of the modelled property, to understand the financial implications of a retrofit to drive the building towards a NZEB, costing analysis is performed. Blanket replacement of all windows would be superfluous given the existing LEB nature of Plas Gwylan; unnecessary expense for the homeowner due to the select influence each glazing type has, hence targeted replacement of windows is considered. This targeted replacement considers three different scenarios, attempting to minimise the heating, cooling and lighting needs of specific zones in the model, with savings metered against a baseline of double glazing. In each case the 3 most energy-hungry zones are retrofitted with the new glazing, with the remainder fitted with double-glazing, Table 5.

Cost of glazing (£/m^2) was determined from online retailers, and other research [57–59]. Implementation cost of each window was considered too, given typical removal and fitting costs in the UK [60], to yield an overall installation cost for each scenario modelled, Equation (2).

$$C_i = C_g + C_r + C_f \tag{2}$$

C_i *is total cost of the installation*

C_g *is cost of glazing*, C_r *is cost of removal*, C_f *is cost of fitting*

To quantify savings, for each scenario a simple Payback Period (PBP) (**Equation (3)**) of the retrofit is included alongside a Net Present Value (NPV) (**Equation (4)**) calculation, to illustrate the financial position of each investment after 25 years. Simple PBP considers the time taken for savings to offset the initial investment, conversely NPV is used to present the value of yearly cashflows given a 3% discount rate [61].

$$PBP\ (years) = \frac{C_i}{S_{p.a.}} \tag{3}$$

$S_{p.a.}$ *are the annual savings of the retrofit*

$$NPV = \sum_{t=0}^{25} \frac{C_n}{(1+D)^t} \tag{4}$$

C_n *is net cash flow in a given year*, D *is discount rate*

For the novel constructs, addition of its constituents was deemed the best approach due to limited commercial production, however it is recognised that these values yield an overestimate, accounting for an

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[1] Savings are determined from UK's OFGEM price cap of £0.34/kWh [63].

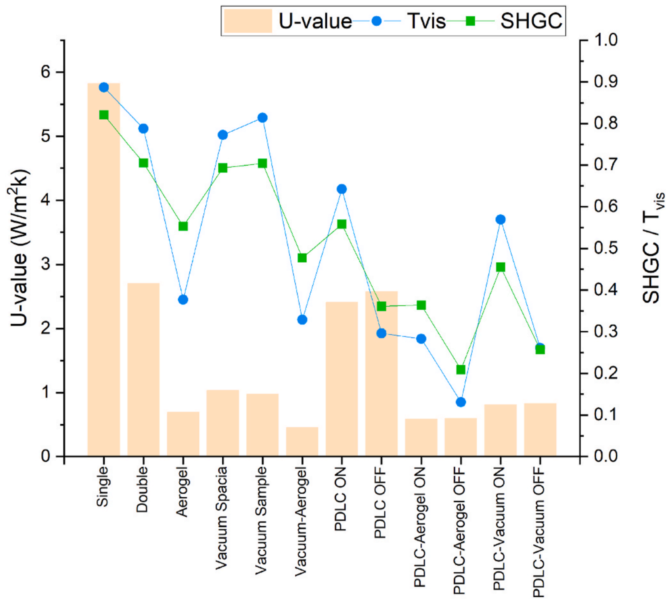

Fig. 6. Modelled constructions' characteristic properties.

extra glass layer.

3. Results and discussion

The following results are categorised according to the scope of results detailed in Fig. 3. Results are typically separated into the advanced glazing technologies i.e., vacuum and aerogel glazing, and smart/switchable glazing (PDLC variants) to provide cross comparisons between constructions.

3.1. WINDOW analysis

The discussed results focus on key terms, *U-value*; a representation of the heat energy lost and Solar Heat Gain Coefficient (SHGC)/*G-value*; a measure of heat energy gain into the building. Visible transmittance (T_{vis}) refers to portion of the visible spectrum that passes through the glazing.

Prior to energy assessment key glazing characteristics are taken from WINDOW and subject to initial inspection. Fig. 6 provides a triple comparison between these characteristics, high *U-value* constructions like single, double and PDLC would require additional heating loads due to their comparatively 'leaky' nature. The vacuum sample and vacuum construction developed in WINDOW show little difference, maintaining high visible transmittance minimising lighting demands, whilst offering improved *U-value*. Conversely the aerogel sample achieved a 33% reduction in *U-value* (compared to vacuum) but compromises on the transmittance, anticipating a reduced heating demand, but increased lighting needs. The sample maintains a *G-value* of 0.552, when coupled with the thermally insulating glassy structure of Plas Gwylan overheating is possible. The coupling of these two technologies in Vacuum-Aerogel offers a 35% reduction in *U-value*, whilst reducing the *G-value* to 0.477 due to the vacuum layer. These reductions are expected to be a slight improvement on the plain aerogel sample, as heat gains are reduced ideally limiting cooling requirement.

Switchable PDLC constructions, in their basic state exhibit high *U-values* (~2.5 W/m^2K), however their tuneable transmission transpires as a 54% reduction in transmission and 35% reduction in *G-value* respectively, between 'on/off' states. In its 'off', translucent, state, lighting requirement would increase in all cases as more diffuse light penetrates the space, cooling likelihood would reduce as unwanted solar heat gains (*G-value*) are reduced. The novel constructions with an aerogel layer reduce the 'swing' in transmission between states, due to the fixed poor transmission of the aerogel layer, irrespective of the PDLC layer's state change. With the addition of a vacuum layer, a similar *U-value* to PDLC-aerogel is achieved whilst maintaining the large swing in transmission between states. Overall performance of building energy is expected to be similar between both novel constructions, with PDLC-aerogel requiring additional lighting, and PDLC-vacuum requiring additional HVAC demands due to its comparatively poorer *U-values*.

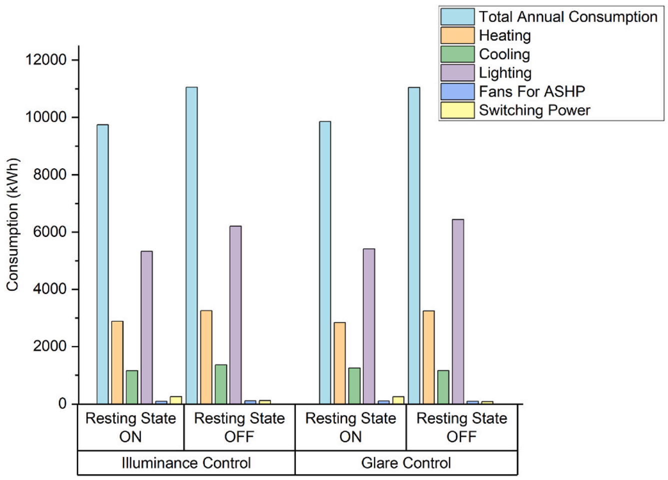

Fig. 7. PDLC glazing control type.

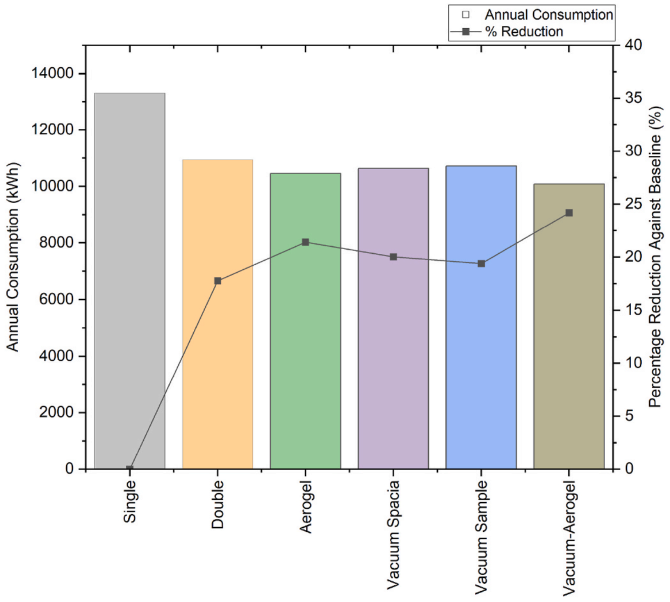

Fig. 8. Percentage reduction of advanced glazing against a baseline of single glazing.

In switchable cases, performance is dictated by control type. For illuminance or glare control, it is important to recognise that there are consequential impacts on the characteristics of the glazing. Whilst the primary function of illuminance control is to meet the setpoints for the occupants, this prioritisation will have consequential impacts on the HVAC demands, most significantly as *G-value* varies. Illuminance control ought to make the best use of daylighting, offering reduced lighting demand, however due to the highly insulative envelope of Plas Gwylan, implementation of the 'best' U/*G-value* constructions could yield additional HVAC demands; exceeding lighting savings offered by illuminance control. As such, there is a balance to strike between lighting demand and HVAC implications when selecting which switchable

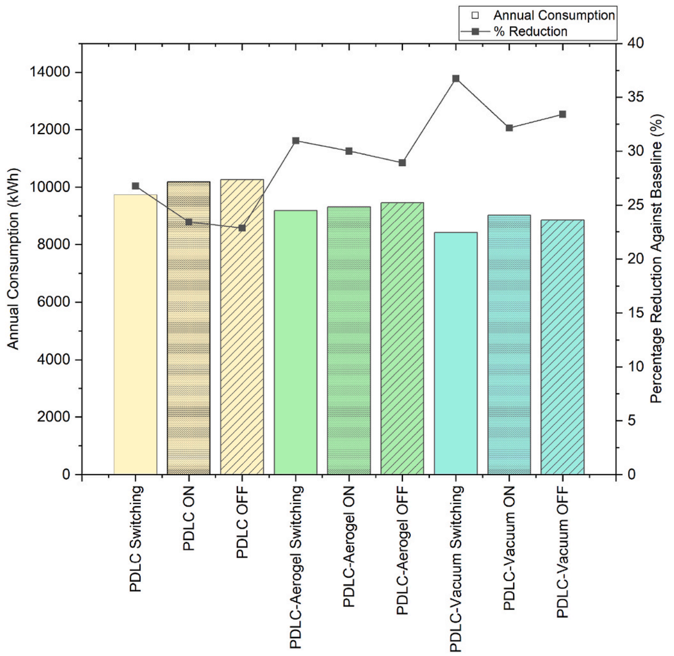

Fig. 9. Percentage reduction of PDLC glazing against a baseline of single glazing.

constructions to pursue. There is an element of subjectivity in this assessment, considering the envelope's construction, orientation and WWR.

Fig. 7 investigates the interactions of switchable window control type for a plain PDLC construct, by varying its resting state. For both control types resting in the 'on' state resulted in the least annual consumption, with illuminance control reducing consumption by 14%–9479 kWh (compared to glare control resting state 'off'). This is due to elevated lighted demands in the 'off' state and increased *U-value* yielding increased heating load to meet the setpoints. Energy from 'switching power' in the 'on' resting states averaged 2.58 times that of the 'off states' indicating that the utilisation of the shade was most effective in the illuminance control cases. Such findings echo that of a similar study for Oman, finding that illuminance, 'daylighting', control was the most effective for PDLC glazing to reduce building consumption [20].

Figs. 8 and 9 illustrate percentage reduction in building energy demand for advanced and switchable glazing respectively, against a baseline single glazing. Replacement with PDLC constructs in their static state is included. Vacuum-Aerogel and PDLC-vacuum switchable performed best in each of their classes, offering a 24% and 37% reduction respectively. In the case of the former this is due to its best-in-class *U-value*, reducing the energy 'hungry' nature of the building's skin, whilst improving on the *G-value*, limiting cooling requirement, sufficiently offsetting additional lighting demand. PDLC-vacuum constructs perform similarly well, with the static 'off' state, outperforming the switching PDLC-aerogel (8859 kWh compared to 9184 kWh). PDLC-vacuum constructions do not offer the best *U-values*; however, this marginal sacrifice is offset since they maintain high transmittance, reducing lighting demand at the expense of heating needs due to increased heat loss. PDLC-Off counters the trend shown in Fig. 9, where typically 'off' static constructions have a reduced consumption compared to their 'on' equivalents. This is due to the polarity between achieving low *U-value* and maintaining high transmission i.e. with the addition of an aerogel layer. For PDLC-vacuum in its 'on' state this dichotomy is challenged, a low *U-value* is achieved without compromise on transmittance. For the low-energy environment of the UK, where highly insulated envelopes are a priority, the comparatively high *G-value* of PDLC-vacuum 'on' (0.455) leads to additional heat gain. Unlike the proposed PDLC-aerogel and aerogel sample, for PDLC-vacuum high transmission comes 'hand-in-hand' with low *U-value*. These results support the development of this construction to a great degree, supporting the conclusions in Ghosh's proposal for the construction [11].

Fig. 10 complements these correlations; despite the improved *U-value* of aerogel, its poor transmission yields significant demands on space lighting, accounting for 56% (5886 kWh) and 60% (6061 kWh) for Vacuum-Aerogel in the advanced window category. Efforts to improve the *U-value* for PDLC successfully reduce heating contribution, and through reduced *G-values* cooling demands are significantly reduced. HVAC demands account for less than a third of building energy demands for PDLC-aerogel and PDLC-vacuum. This suggests that the building is inherently more passive, reaching a thermal state of 'equilibria', where external heating/cooling inputs are diminished. So much so that just 1065 kWh of heating, 160.8kgCO_2, is required for PDLC-vacuum when switching. This is a 60% reduction compared to double glazing,

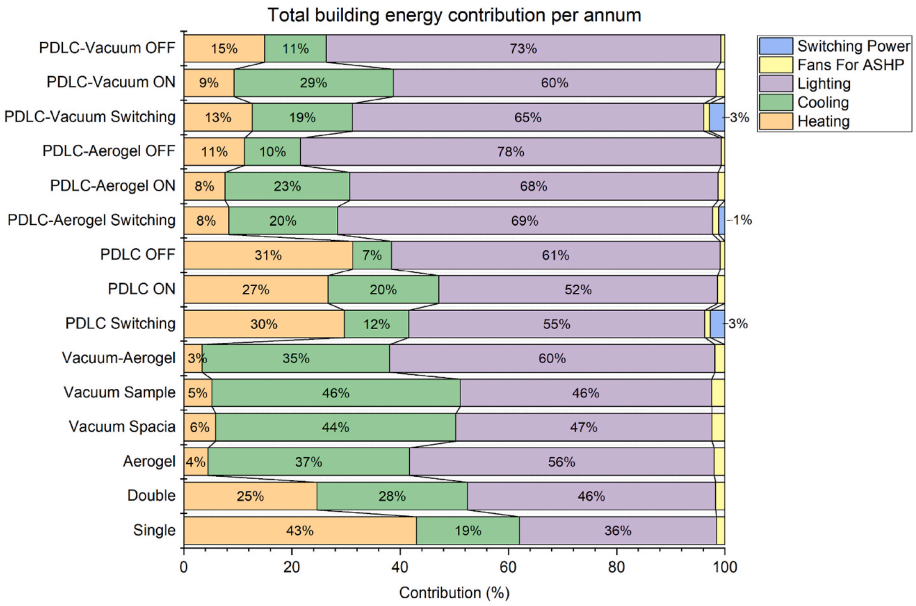

Fig. 10. Percentage contribution of building energy consumption for all glazing samples.

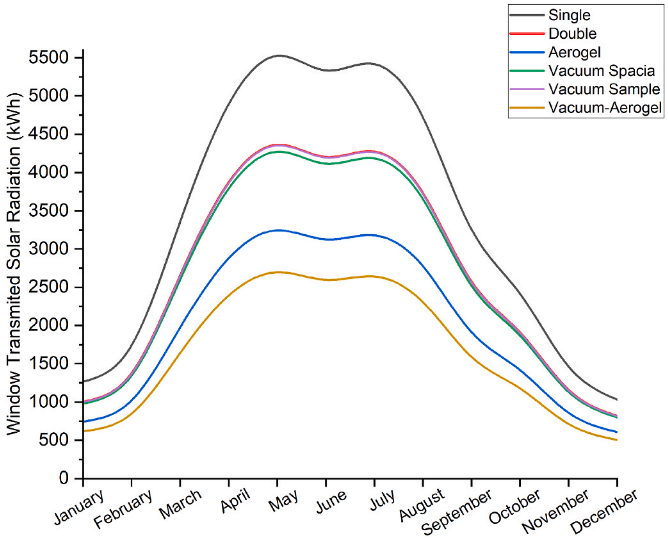

Fig. 11. Monthly variance of transmitted solar radiation for advanced glazing.

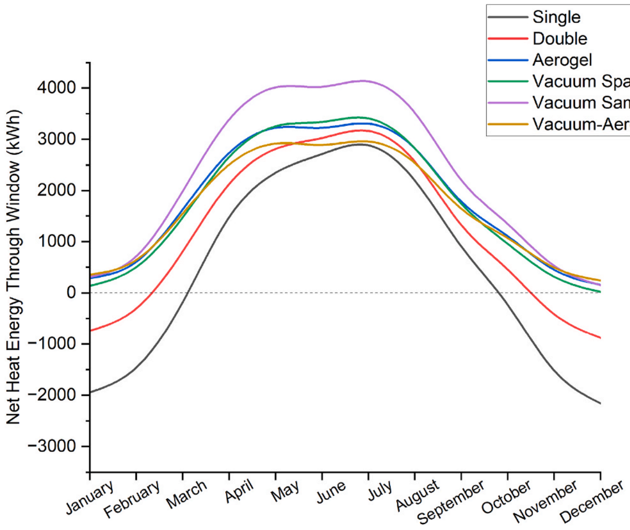

Fig. 14. Monthly variance of window heat energy for advanced glazing.

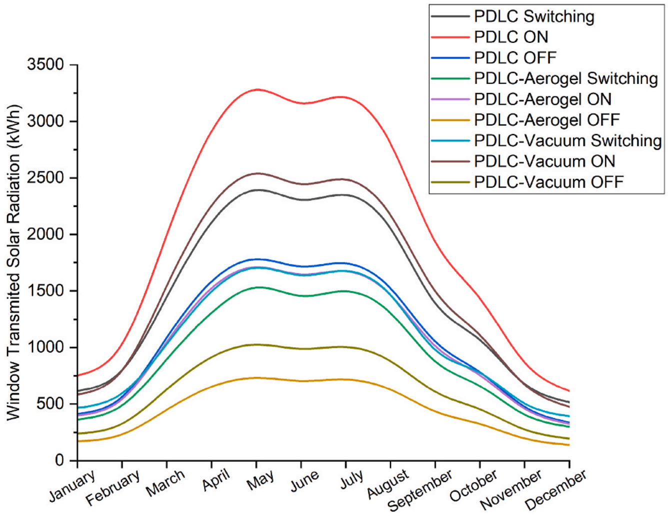

Fig. 12. Monthly variance of transmitted solar radiation for PDLC glazing.

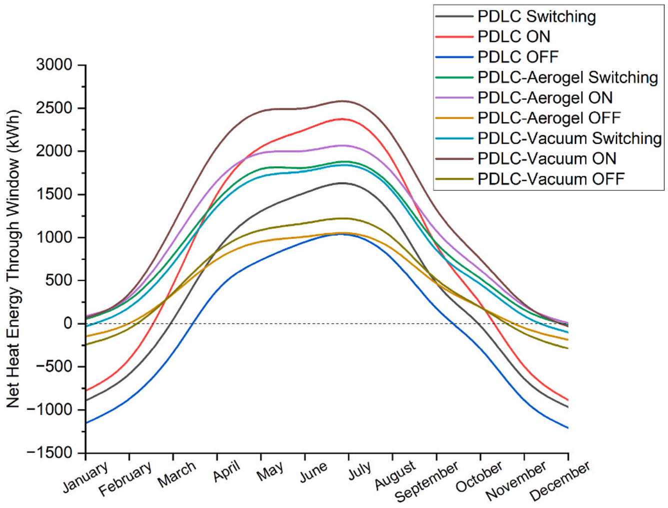

Fig. 15. Monthly variance of window heat energy for PDLC glazing.

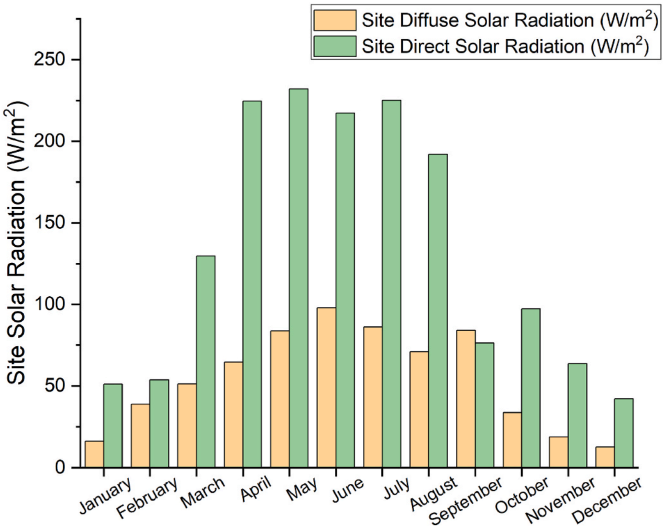

Fig. 13. Site solar radiation variance.

constructions prevalent in the UK's housing stock [9].

Figs. 11–13 illustrate transmitted solar radiation for all constructs, and incident radiation at the site. Attributed to *G-value*, transmitted solar radiation is critical to consider. Solar radiation transmission is important to consider as it has consequential impacts on HVAC demands, whilst energy efficient in principle, these demands can translate to unnecessary CO_2 emissions and costs to the homeowner. Advanced glazing exhibits a greater seasonal range than that of PDLC constructs, with Vacuum-Aerogel illustrating the smallest amount of seasonal range of 2190 kWh. Peaking at 2695 kWh, this exceeds the peak summer gain of PDLC constructs, except of PDLC 'on' at 3280 kWh. This peak correlates to the increased site radiation for the summer periods due to the *G-value* of 0.558 for PDLC 'on', the highest in the switchable class. **This** means elevated space cooling needs as incident radiation warms the space and its objects, warming the space beyond a comfortable range particularly in the summer months (April–August) where radiation and ambient temperature are higher.

Fig. 13 demonstrates a significant increase in direct solar radiation increasing by 141% from February to March and a further 73% increase to April. This transition is mimicked by the glazing, particularly in the PDLC derived 'on' states. However, the 'off' states are notably resilient to this shift with PDLC-aerogel 'off' providing the 'steadiest' year-round

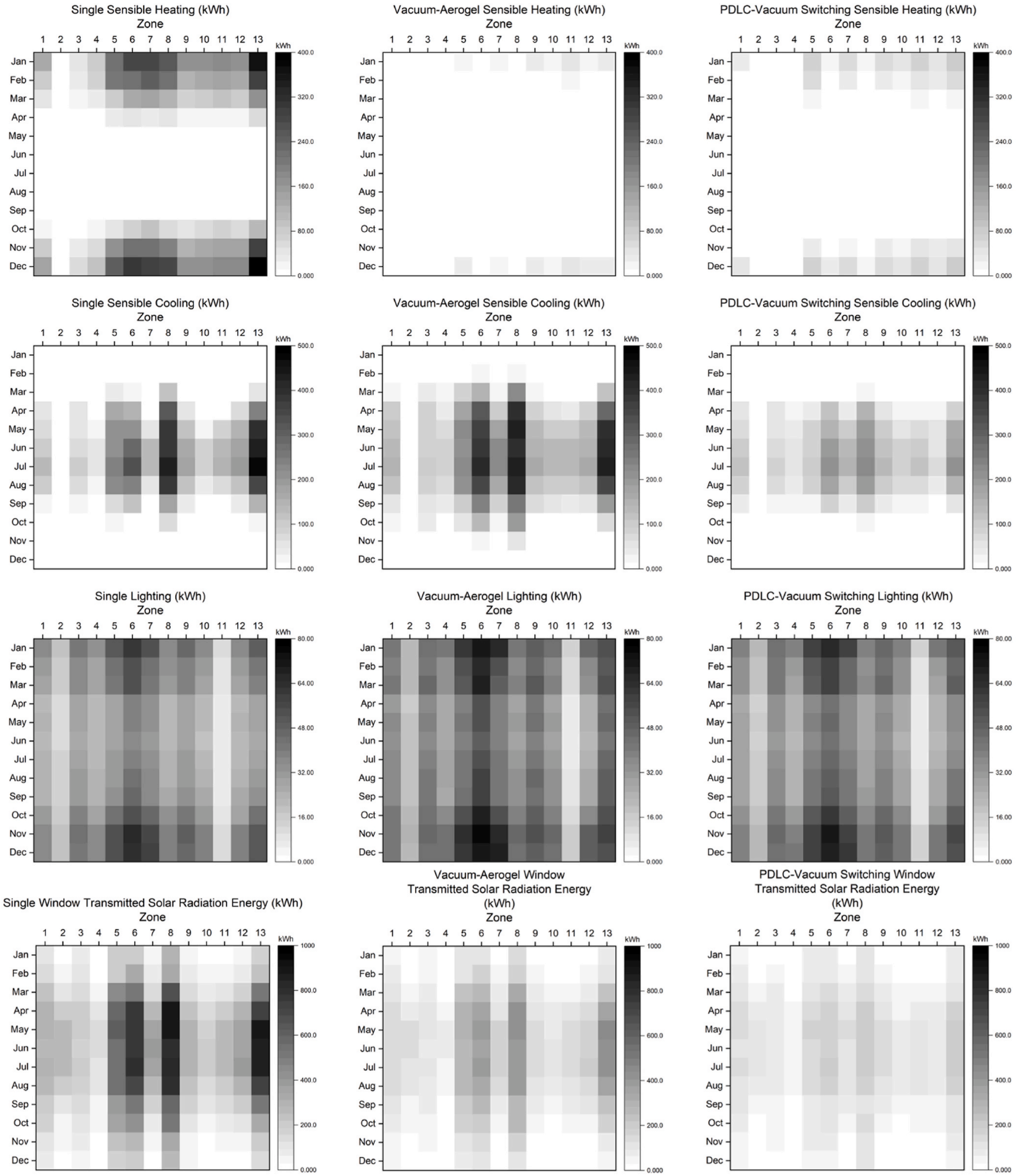

Fig. 16. Zonal heat maps for vacuum-aerogel and PDLC-vacuum, against a baseline of single glazing.

transmission of solar radiation; characterised by its horizontally stretched sinusoidal shape. Whilst this characteristic may be desirable in some applications, e.g. glassy south facing facades, notably the skylights and French doors on Plas Gwylan, the lower transmission of radiation in the energy hungry winter/autumn months in undesirable, resulting in additional electrical demands and CO_2 emissions. Similarly, the hybrid PDLC constructions in their switching state attenuate these extremes in transmitted radiation, demonstrated across all constructions, Fig. 12. They limit heat gain through their low *G-values*, useful in the summer months reducing cooling demands, whilst maintaining a higher influx of radiation in the heating-hungry winter months – further reducing reliance on HVAC needs.

Figs. 14 and 15 consider net heat energy through the glazing, presenting a sum of heat gains minus heat losses. Consider the baseline at 0

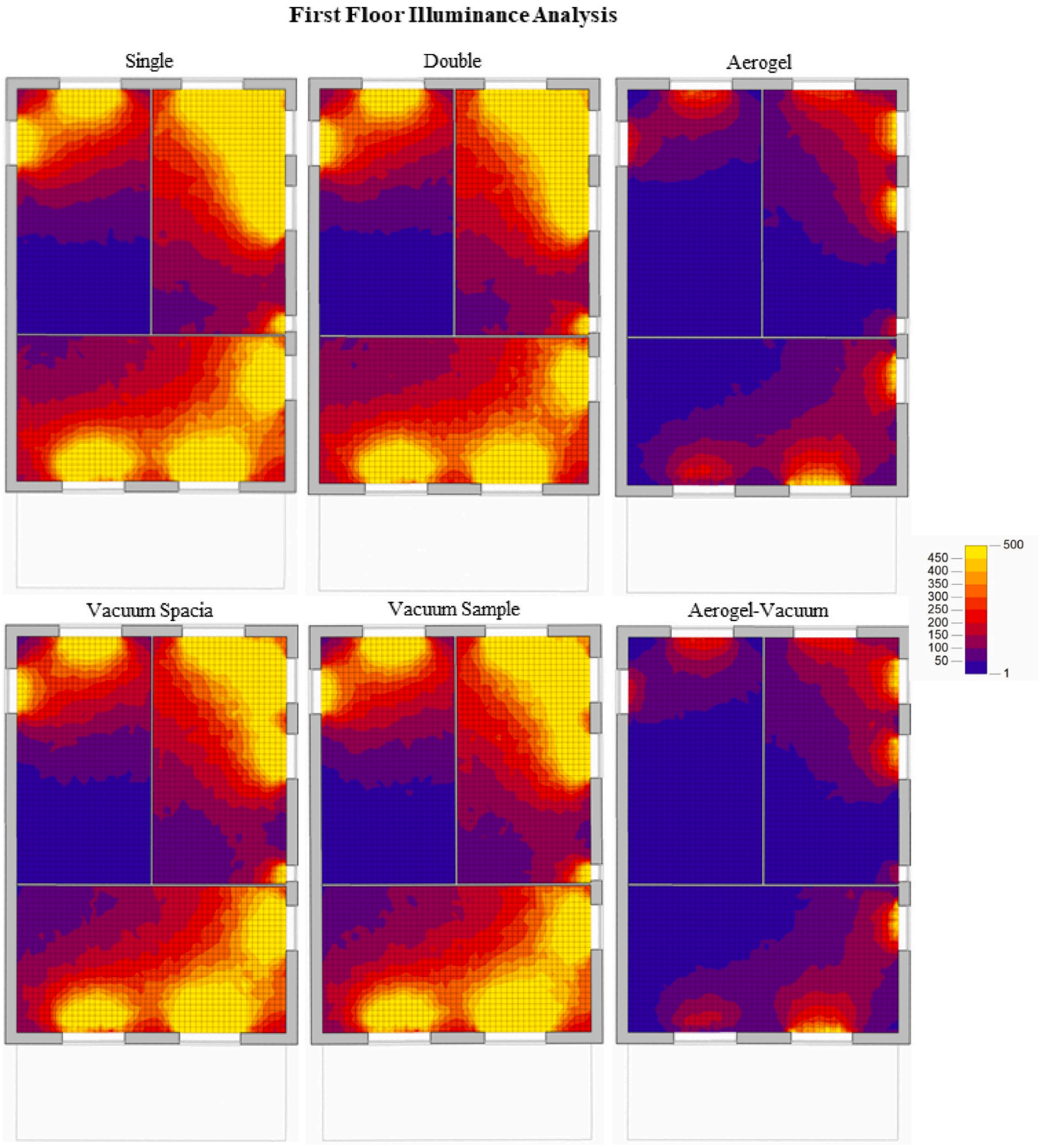

Fig. 17. Illuminance simulation for advanced glazing.

kWh, all proposed advanced glazing systems present a year wide positive gain of heat energy through the glazing (Fig. 14). The vacuum sample exhibits the greatest annual range of these, accounting for 4128 kWh of heat gain in July, and just 151 kWh in December. However, given the discussed likelihood of overheating of the property, particularly on the predominantly south-facing rear façade, heat gain in the summer months to this extreme could be unwanted. In the winter months, all advanced constructions are tightly clustered. Consider the performance of vacuum-aerogel, which offers the greatest heat gain in heating-hungry winter months, reducing demand, also accounts for a maximum heat gain of 2916 kWh in May, a 29% decrease compared to the vacuum sample's maximum. This due to its 'best-in-class' *U* and *G-value*, hence shallower rate of net heat gain throughout the year is observed. This yields less dramatic increases in cooling and heating loads, enabling the property to the be more 'passive' and resilient in its operation.

Fig. 15 is more complex, the poor *U-value* of plain PDLC constructs results in an approximately 6 months of the year 'leaking' heat energy - challenging in the low energy environment of the UK; an unnecessary form of heat energy waste. In their switching states the PDLC hybrid constructions closely follow one another, despite their respective differences in *U* and *G-value*. PDLC-aerogel switching, despite its ability for low *G-values*, suggests that for much of the summer significant periods are spent in its 'on' state to meet illuminance needs, which in turn leads to greater solar heat gains. Similarly, PDLC-vacuum switching follows a near identical pattern, conveying a similar behaviour, however net heat gains are reduced due to its higher *U-values* (increased heat loss from the building), despite its comparatively higher *G-values*. In their switching form, the PDLC-hybrid constructions serve as a midpoint between the two extremes of the 'on' and 'off' states, which when static are not well suited to year-round functionality. Notably, the 'off' states of the PDLC hybrids are disappointing in the winter months, however their

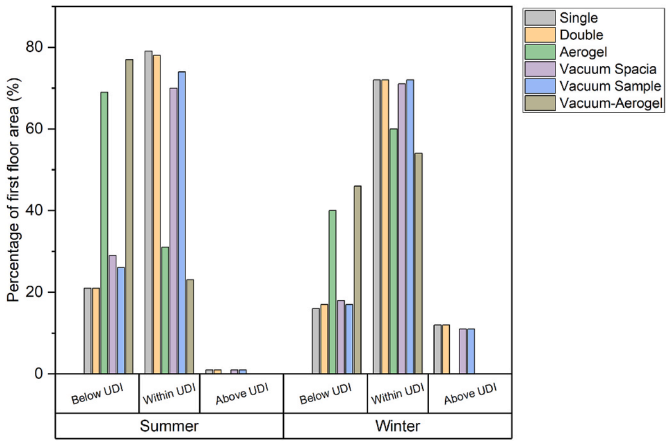

Fig. 18. UDI of the first floor for the summer and winter solstice with advanced glazing.

attenuated shape suggests that they are beneficial to equilibrate the particularly glassy areas of the building; preventing overheating in summertime heatwaves, important to consider given the hot summer of 2022 [62].

Given the continued performance of Vacuum-Aerogel and PDLC-vacuum, Fig. 16 examines their performance zonally against a baseline of single glazing. It is evident that the sensible heating and cooling demands are broadly spread across each zone, with the heating demands of the PDLC-vacuum extending further throughout the year and Vacuum-Aerogel's cooling needs extending into February and November. Despite the reduced intensity of cooling demand for PDLC-vacuum compared to Vacuum-Aerogel, 'hotspots' are evident. Zones 6,8 and 13 demonstrates significant thermal 'strain' on the building. This is due to the south facing orientation of the latter two and glassy facade, with high WWRs i.e., 19.8% for zone 8. This is exacerbated with the seasonal sunlight utilising the skylights in zone 13, likely causing overheating.

Lighting demand follows a similar pattern, with the winter months of Vacuum-Aerogel being particularly demanding for zones 5,6,7 – ground and first floor zones of poor orientation and low WWR resulting in suboptimal daylight penetration. In both novel cases, lighting demand is increased compared to the baseline, despite the high transmission of PDLC-vacuum in its 'on' state, emphasising the consequences of managing illuminance levels for occupants.

Transmitted solar radiation plots reduce in intensity as *G-value* decreases, reducing the seasonal 'swing' in transmitted energy. This has a causal relationship with the heating and cooling loads placed on Plas Gwylan, as the heating and cooling plots respond to window's heat addition to the space. Despite similarities between each other, it is evident that PDLC-vacuum offers remarkable savings in its switchable state with resilience to seasonal swings in radiation and temperature. Its ability to limit transmitted radiation offers a particular reduction in sensible cooling energy requirement, whilst reducing lighting needs compared to vacuum-aerogel due to its 'tuneable' transmission. And as such nets an annual emission of 1480 kgCO_2, compared to 1826 kgCO_2 for Vacuum-Aerogel.

3.2. Daylighting modelling

Figs. 17–20characterise a daylighting assessment of the first floor of the property. For all of the evaluated constructions, daylighting penetration is considered on the summer solstice at midday as well as a UDI threshold assessment for the same area, including the winter solstice as well.

Fig. 17 considers the illuminance mapping of the advanced glazing. Overall, the lower transmittance of aerogel derived constructions yielded a dramatic reduction in illumination level, with only the near vicinity of each window providing near workable lighting conditions. The vacuum derived glazing showed little difference between the sample and WINDOW model. Performance of these glazings was on-par with that of double glazing, however the uniformity of the illuminance was poor, with highly concentrated areas of the room well-lit with the others at <100lx – clearly illustrated in the darker corners of the rooms modelled. Conversely the Aerogel sample whilst yielding a low illuminance level, offers more uniform 'ambient' lighting, which would improve the visual comfort of the occupants with negligible likelihood of glare issues – an anticipated issue for other glazings with great concentrations of >300lux areas. This is characterised by orange and yellow sectors, clearly demonstrated for the southerly room, zone 8.

For the same constructs, Fig. 18 quantifies these results. Generally Vacuum glazing offers the better UDI for both seasons, with a marginal reduction on the baseline single and double glazing examples. Aerogel on the other hand, is challenged with only 31% within the 100–2000lx threshold in the summer, a 43% reduction on the vacuum sample. However, this difference is decreased to 12%, with 60% of the floor area satisfied in the winter period, as the sun's path changes. Greater daylight penetration is apparent, with significant exceedance of UDI likely to cause glare issues for occupants in the vacuum case, an issue that does not trouble aerogel constructions. These benefits of aerogel derived constructions are advantageous, as the heating-hungry winter periods are further benefitted by its low *U-value*.

Fig. 19 considers the switchable constructs evaluated in their 'on' and 'off' states. The effectiveness of traditional PDLC, like the sample modelled here, is clearly exemplified. In its 'off' state plain PDLC reduces daylight penetration offering more uniform illuminance at a reduced intensity. Going further with the addition of an aerogel layer, in its 'on' state is nearly equivalent to a plain PDLC glazing in its 'off' state, with a similar floor area lit to 50–150lx. PDLC-vacuum offers an 'attenuated' version of plain PDLC for both sates, notably more uniform daylighting of reduced intensity near windows in its 'on' state for the 150–300lx range.

Fig. 20 supports this, as in the 'off' state area below UDI increases. This increase is most profound in the PDLC-vacuum case, area below UDI threshold increases by 37% between 'on' and 'off' states, compared to 14% for PDLC-aerogel (in summer). This is due to the poor 'swing' in transmission between states as previously discussed. In the summer period PDLC-aerogel performs vastly differently to the winter, with the latter being arguably the most useful application of the technology due to its low *U-values*. In winter a UDI swing of 28% is observed between states, however only 43% is satisfied in its 'on' state. Conversely the seasonal difference between PDLC-vacuum is most stark in its 'off' state, with 17% of floor area satisfied in summer compared to 45% in winter. It should be noted that exceedance of the UDI is possible for this construction in wintertime, potentially leading to excessive illuminance or glare. In these cases, large areas of floor are satisfactorily lit, with the switchable window offering limited reductions in illuminance. Implementation of PDLC-vacuum offers the greatest year-wide application better utilising summer daylighting, despite the risk of exceeding UDI in winter. These results place particular emphasis on room orientation, and WWR. Strategic thinking ought to consider the placement of windows given façade orientation, seasonal variance of sun elevation angle, and space use which should also be considered with differing room function as required illuminance differ. This consideration would ensure appropriate, targeted, use of the technology.

4.1. Sensitivity analysis: orientation & window-to-wall ratio

Further assessment of building orientation and window-to-wall ratio (WWR) is considered. Orientation is significant and has consequential impacts on building HVAC demands as well as lighting needs, and for this analysis refers to the orientation of the front, entrance façade, relative to north. In the northern hemisphere, and the low-energy environment of the UK, south facing facades are favourable due receiving increased sunlight, yielding increased solar heat gains,

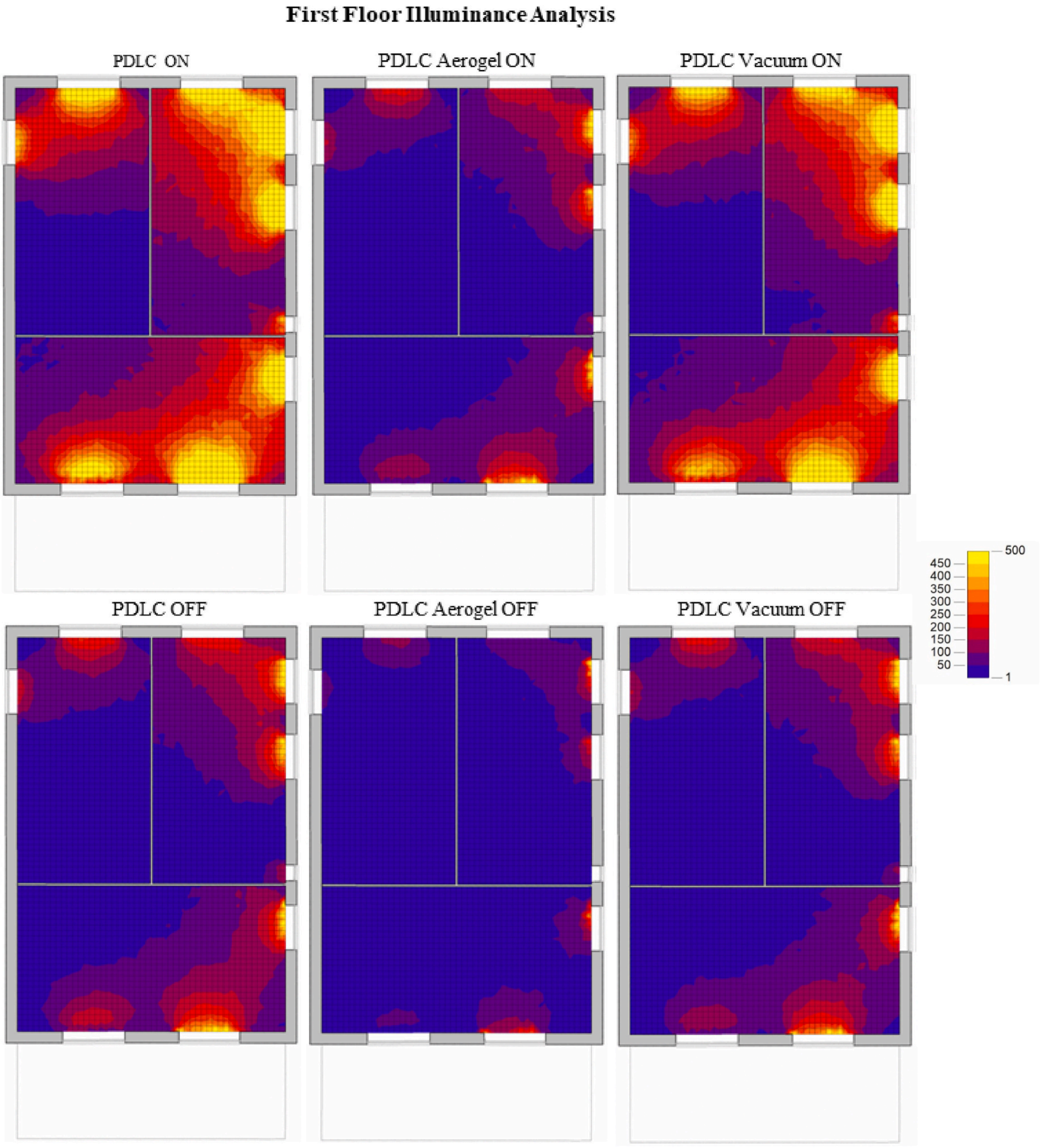

Fig. 19. Illuminance simulation for PDLC glazing.

warming the property. Similarly, WWR is of consideration, and refers to the ratio of glazed fenestration to gross exterior wall area. A compromise arises whereby increased WWR can provide increased daylight, but also yield increased solar heat gains, increasing the likelihood of overheating. External wall thermal resistance is challenged as well, for increasing WWR with comparatively poorer *U-values*, increases the ‘leakiness’ of the building skin, typically making it more ‘energy hungry’.

For this analysis, the best performing glazing for each of the classes was considered, Vacuum-Aerogel and PDLC-vacuum switching. The building’s main energy consuming elements are subject to this analysis. The existing WWR was considered, 14.5%, and windows were scaled to reflect a 5% increase and decrease in overall WWR: WWR 19.5% and 9.5% respectively. Fig. 21 illustrates heating demand for both constructs, it is evident that orientation towards the south yields increased heating demands. Despite illuminance controlled PDLC-vacuum glazing, the front façade of the property, with an original low WWR of 15%, limits solar heat gains, compared to the rear of the property with an original WWR of 25%. When orientated north, the rear of the property enjoys these southerly heat gains, significantly reducing heating demand by 28% for a building WWR of 19.5% compared to when the building is oriented southerly and high WWR rear facade is facing north. Interestingly the significance of WWR does not correlate between Vacuum-Aerogel and PDLC-vacuum. Reduced glazing in the aerogel case yields increased heating need compared to PDLC-vacuum. Most significantly as the glassy facade is orientated southerly, the high *G-value* alongside an insulative *U-value*, means that the building skin is significantly less heating-hungry as solar heat gains are greater as WWR increases.

Whilst the orientation response is similar for PDLC-vacuum, heating demand is particularly sensitive to WWR, when oriented southerly increasing the WWR 14.5%–19.5% yields a 17% increase in demand, an

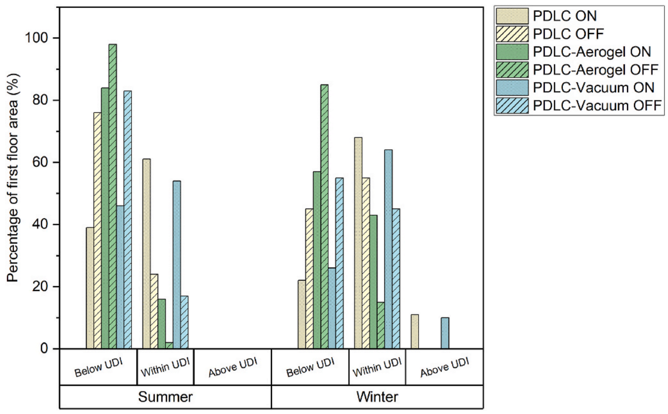

Fig. 20. UDI of the first floor for the summer and winter solstice with PDLC glazing.

additional 42 kgCO$_2$. Its solar heat gains are clearly limited through the illuminance shading control, despite increasing WWR.

Most notable is PDLC-vacuum when poorly orientated, i.e. the façade with the lowest WWR faces southerly. Despite an overall high WWR, this poor orientation means that the comparatively poorer *U-value* of the constructions compromises the space heating needs of the building. Few benefits are offered, as daylighting is limited, solar heat gains are minimal, and the skin is more leaky. A delicate balancing act ensues, recognising that targeted fitment of this glazing is required, illustrating that there is an optimal WWR and orientation for deployment. As such, the priority of the installation should be considered – either targeting space heating/cooling requirement or lighting consumption.

Fig. 22 illustrates a similar concept, except challenged by the excessive retention of heat due to the low *U-values* of the glazing. Through increased WWR, particularly when orientated north, leaving the rear façade exposed to extensive solar radiation, the cooling load increases too. PDLC-vacuum was more effective at mitigating overheating risk through a 45% increase in cooling load from WWR 14.5%–19.5%. Whereas the even lower *U-value* vacuum-aerogel, and a higher *G-value* of 0.477, notably struggled, seeing a 56% increase for the same WWR range. It can be inferred that replacement of glazing with this construction should be targeted to low WWR spaces, where decreased heating loads are desired, and orientated southerly. However, this relative increase in cooling load dramatically exceeds the heating

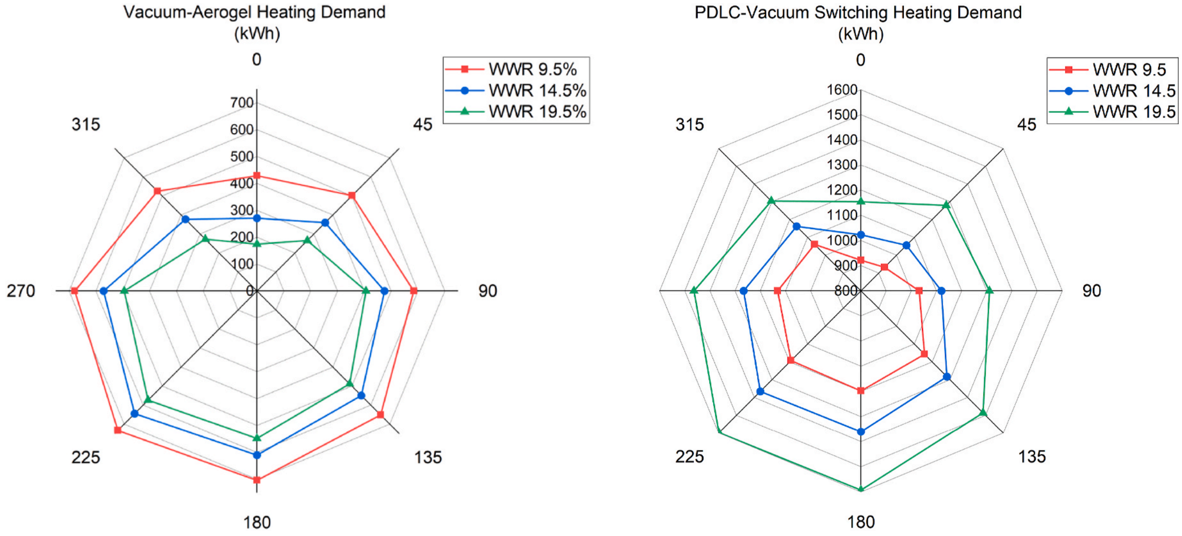

Fig. 21. Variance in space heating needs for varying WWR and orientation, respect to north.

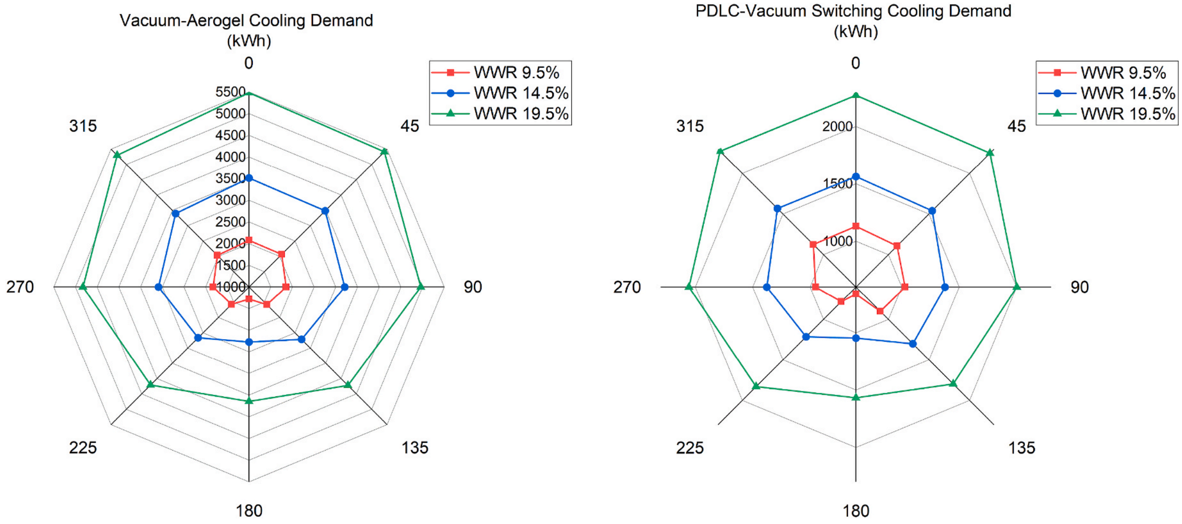

Fig. 22. Variance in space cooling needs for varying WWR and orientation, respect to north.

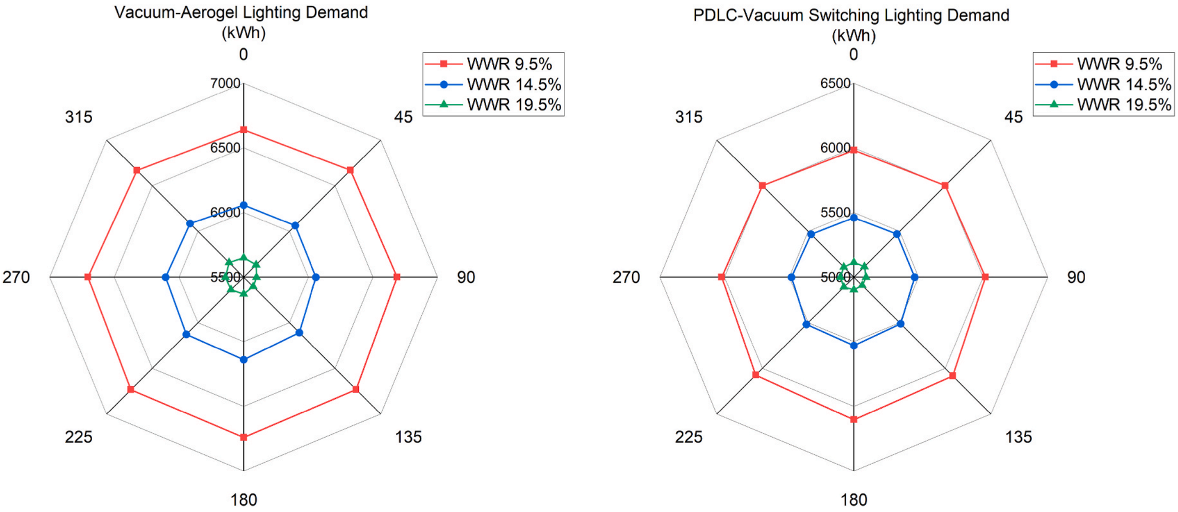

Fig. 23. Variance in space lighting needs for varying WWR and orientation, respect to north.

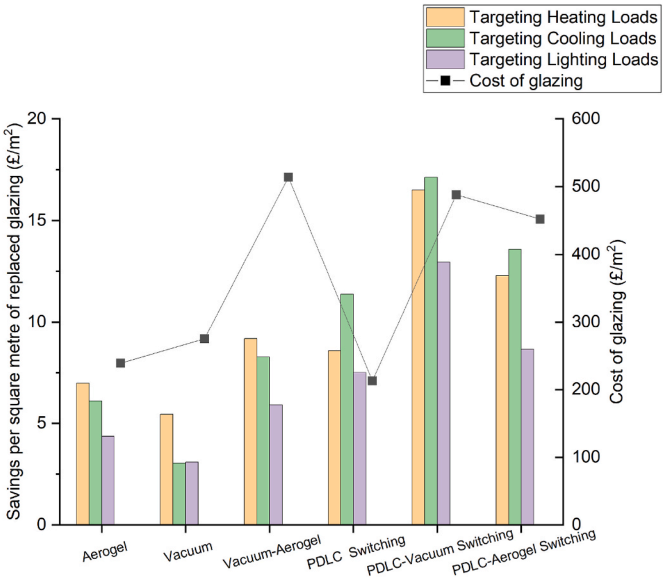

Fig. 24. Illustrates the financial savings of this targeted fitment, compared to a fully double-glazed envelope.

savings illustrated in Fig. 21, a reduction of only 62 kWh from WWR14.5–19.5 at 180° Awareness of this varied response is critical to successfully deploying aerogel derived glazing.

Fig. 23 cements a heating-cooling-lighting trilemma, conveying the significance that increased WWR can have at reducing lighting load. Interestingly there is little discernible difference between the percentage reduction in lighting demand for both constructions as WWR increases from 14.5% to 19.5%; 6.7% and 6.3% for Vacuum-Aerogel and PDLC-vacuum respectively. Consider the marginal benefits of orientating your building façade with the most glazing (rear facing) southerly to decrease lighting needs, more clearly expressed for the PDLC-vacuum instance.

4.2. Costing analysis

Fig. 24 Targeted replacement of windows in energy-hungry specific zones.

It is evident that targeting the high cooling loads yielded the most significant savings in the advanced window case. For the smart windows, targeting cooling-hungry zones yielded the greatest savings, particularly for PDLC-vacuum, saving £17.13/m^2 (£532[4] in savings p. a.), however this hybrid construction typically comes at higher cost, an estimated 2.3 times that of a plain PDLC construction. This is explained

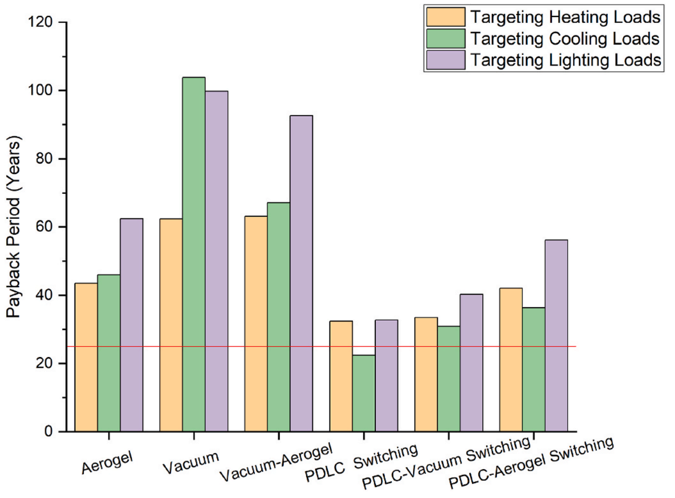

Fig. 25. Simple PBP for targeted replacement.

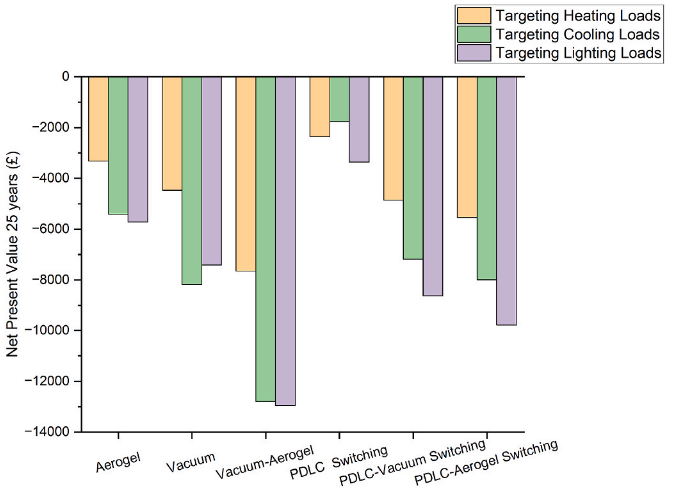

Fig. 26. NPV after 25 years for targeted replacement.

as the cooling hungry zones are typically more glassy (Table 4) and the switchable nature of smart windows, by modulating daylighting, in-turn limits solar heat gains; a two-fold response.

Consider Fig. 25 illustrating simple PBP, given the varied quantity of replaced glazing, the cost of glazing and respective energy savings, it is apparent that only the smart windows offer a reasonable payback period of 20–30 years. Careful consideration is required with this targeted retrofit; the impact of window replacement for some constructions is profound, whereas the seemingly cheaper, low *U* and *G-value* constructions i.e. aerogel, yield increased payback period. A more detailed approach to calculating glazing cost of the novel constructions, PDLC-vacuum etc, would yield reduced material costs, and would likely stress their suitability.

Conversely Fig. 26 NPV of each retrofit after 25 years, illustrates the nuances of varied savings with respect to investment; where targeting heating loads yielded the best NPV in all cases, apart from plain PDLC. The discussed low PBP of smart windows when targeting cooling loads does not materialise to a great NPV over the 25-year period. This is due to the coupled nature of the hybrid construction; high glazing cost comes hand-in-hand with high annual savings. This means after a lifespan of 25 years, a financial loss remains. From a financial standpoint, the aerogel and PDLC constructions are the soundest investment, however if considering carbon impacts this view would differ.

4. Conclusion

Given the carbon-intensive buildings sector pretext, retrofit of advanced and smart/switchable windows for a LEB was considered. This work set out to develop an understanding of the implications alternative windows had on building energy consumption. Key findings can be summarised as:

- EnergyPlus simulation with foreground data from previous works revealed a net energy saving of 2663 kWh and 2849 kWh for vacuum and aerogel glazing respectively, compared to a baseline of single glazing. Attempting to improve on this, the addition of a vacuum layer to the aerogel sample was considered, this reduced aerogel's demand by a further 3.5%.
- Traditional PDLC smart window, when switching, reduced building energy demand by 28.8% and following recent literature, the addition of a vacuum layer was considered, yielding a 13.7% reduction. This construction performed best in the smart/switchable window class.
- Going further, daylighting analysis revealed seasonal differences in UDI of each construction. PDLC-vacuum revealed high UDI in the winter months, peaking at 64% and 45% within the threshold for its 'on' and 'off' states respectively. Seasonal exceedance of UDI is anticipated for PDLC-vacuum. Limited applicability of aerogel for daylighting was highlighted, the maximum UDI of 31% in summer was down to its poor visible transmission.
- The sensitivity of building orientation was particularly acute for PDLC-vacuum, revealing that building orientation can vary heating and cooling needs by upto 38% and 41% respectively. Its sensitivity to WWR was also greater than the best performing advanced window of vacuum-aerogel. A low WWR of 9.5% revealed minimal HVAC demands for vacuum-aerogel, at the expense of increased lighting needs due to the low opportunity for daylighting.
- Cost analysis revealed distinct challenges when retrofitting of these constructions. Plain PDLC was the only construction able to achieve a payback period <25 years due to its low cost. Out of all tested constructions targeted fitment of PDLC-vacuum yielded the greatest savings at £17/m^2 pa.

Following these results, a prioritisation trilemma has emerged between optimisation of heating, cooling or lighting needs. Crucially this work revealed that PDLC-vacuum offered the best savings across all three categories. The role of advanced windows however should not be lost and are still suited to spaces with other differing demands. And as such the LEB nature of Plas Gwylan stresses the significance smart windows can have in driving a LEB closer towards a ZEB.

5. Future scope

Future scope ought to focus on further development of PDLC-vacuum given its significance in these findings, particularly for cold climates, like that of the UK. Notably development of an experimental prototype should be considered, and critically compare its characteristics to the theoretical construction proposed in this work. Such a prototype should also undergo field testing to comparing performance and energy savings observed in this study.

PDLC-vacuum's applicability, alongside advanced window like aerogel, in a variety of building types, ranging different ages and HVAC services would also be of particular interest to take steps towards NZEBs. Such further research would address one key limitation of this work; the LEB nature of Plas Gwylan limits the breadth of these findings given the wide range of building types and ages of the UK housing stock. Performance of the sampled constructions ought to be investigated for comparable LEBs in alternate climates as well, notably for the modulation of cooling load in hot climates.

CRediT authorship contribution statement

Edward Field: Data curation, Formal analysis, Investigation, Methodology, Resources Software, Validation, Writing – original draft. **Aritra Ghosh:** Conceptualization, Funding acquisition, Project administration, Resources, Supervision, Visualization, Writing – review & editing.

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.

Data availability

Data will be made available on request.

References

[1] Chegari B, Tabaa M, Simeu E, Moutaouakkil F, Medromi H. An optimal surrogate-model-based approach to support comfortable and nearly zero energy buildings design. Energy 2022;248. https://doi.org/10.1016/J.ENERGY.2022.123584.

[2] Park BR, Chung MH. Analysis of the additional energy-saving potential of residential buildings after mandatory zero-energy buildings to achieve carbon neutrality in South Korea. Build Environ 2023;228:109908. https://doi.org/10.1016/J.BUILDENV.2022.109908.

[3] United Nations. United Nations Sustainable Development Agenda n.d. https://www.un.org/sustainabledevelopment/development-agenda-retired/(accessed April 13, 2023).

[4] United Nations Environment Programme. Goal 11: Sustainable Cities and Communities | Unep - Un Environment Programme N.D. https://www.unep.org/explore-topics/sustainable-development-goals/why-do-sustainable-development-goals-matter/goal-11 (accessed April 13, 2023).

[5] The World Bank. Tracking Sdg 7 The Energy Progress Report 2020 n.d. https://www.irena.org/-/media/Files/IRENA/Agency/Publication/2020/May/SDG7Tracking_Energy_Progress_2020.pdf (accessed April 13, 2023).

[6] Skillington K, Crawford RH, Warren-Myers G, Davidson K. A review of existing policy for reducing embodied energy and greenhouse gas emissions of buildings. Energy Pol 2022;168:112920. https://doi.org/10.1016/J.ENPOL.2022.112920.

[7] Alabid J, Bennadji A, Seddiki M. A review on the energy retrofit policies and improvements of the UK existing buildings, challenges and benefits. Renew Sustain Energy Rev 2022;159:112161. https://doi.org/10.1016/J.RSER.2022.112161.

[8] Office for National Statistics. Age of the property is the biggest single factor in energy efficiency of homes - office for National Statistics. Census 2021. 2021, https://www.ons.gov.uk/peoplepopulationandcommunity/housing/articles/ageofthepropertyisthebiggestsinglefactorinenergyefficiencyofhomes/2021-11-01.

[9] UK Government. Net zero strategy. Build Back Greener; 2021.

[10] Khaled Mohammad A, Ghosh A. Exploring energy consumption for less energy-hungry building in UK using advanced aerogel window. Sol Energy 2023;253:389–400. https://doi.org/10.1016/J.SOLENER.2023.02.049.
[11] Ghosh A. Investigation of vacuum-integrated switchable polymer dispersed liquid crystal glazing for smart window application for less energy-hungry building. Energy 2023;265:126396. https://doi.org/10.1016/J.ENERGY.2022.126396.
[12] Vasquez NG, Rupp RF, Andersen RK, Toftum J. Occupants' responses to window views, daylighting and lighting in buildings: a critical review. Build Environ 2022;219:109172. https://doi.org/10.1016/J.BUILDENV.2022.109172.
[13] Jiang Y, Li N, Yongga A, Yan W. Short-term effects of natural view and daylight from windows on thermal perception, health, and energy-saving potential. Build Environ 2022;208:108575. https://doi.org/10.1016/J.BUILDENV.2021.108575.
[14] Bian Y, Chen Y, Sun Y, Ma Y, Yu D, Leng T. Simulation of daylight availability, visual comfort and view clarity for a novel window system with switchable blinds in classrooms. Build Environ 2023;235:110243. https://doi.org/10.1016/J.BUILDENV.2023.110243.
[15] Statista. England housing insulation | statista. 2023. https://www.statista.com/statistics/292265/insulation-in-dwellings-in-england-uk-y-on-y/.
[16] Hm Government. The building regulations 2010 conservation of fuel and power Part L1A. 2013.
[17] Boyano A, Hernandez P, Wolf O. Energy demands and potential savings in European office buildings: case studies based on EnergyPlus simulations. Energy Build 2013;65:19–28. https://doi.org/10.1016/J.ENBUILD.2013.05.039.
[18] Foda E, El-Hamalawi A, Le Dréau J. Computational analysis of energy and cost efficient retrofitting measures for the French house. Build Environ 2020;175:106792. https://doi.org/10.1016/J.BUILDENV.2020.106792.
[19] Pereira W, Bögl A, Natschläger T. Sensitivity analysis and validation of an EnergyPlus model of a house in upper Austria. Energy Proc 2014;62:472–81. https://doi.org/10.1016/J.EGYPRO.2014.12.409.
[20] Chidubem Iluyemi D, Nundy S, Shaik S, Tahir A, Ghosh A. Building energy analysis using EC and PDLC based smart switchable window in Oman. Sol Energy 2022;237:301–12. https://doi.org/10.1016/J.SOLENER.2022.04.009.
[21] Wang L, Gwilliam J, Jones P. Case study of zero energy house design in UK. Energy Build 2009;41:1215–22. https://doi.org/10.1016/J.ENBUILD.2009.07.001.
[22] Ghosh A, Norton B. Advances in switchable and highly insulating autonomous (self-powered) glazing systems for adaptive low energy buildings. Renew Energy 2018;126:1003–31. https://doi.org/10.1016/J.RENENE.2018.04.038.
[23] Ghosh A. Diffuse transmission dominant smart and advanced windows for less energy-hungry building: a review. J Build Eng 2023;64:105604. https://doi.org/10.1016/J.JOBE.2022.105604.
[24] Wu S, Sun H, Duan M, Mao H, Wu Y, Zhao H, et al. Applications of thermochromic and electrochromic smart windows: materials to buildings. Cell Rep Phys Sci 2023:101370. https://doi.org/10.1016/J.XCRP.2023.101370.
[25] Gorgolis G, Karamanis D. Solar energy materials for glazing technologies. Sol Energy Mater Sol Cell 2016;144:559–78. https://doi.org/10.1016/J.SOLMAT.2015.09.040.
[26] Sun Y, Wilson R, Liu H, Wu Y. Numerical investigation of a smart window system with thermotropic Parallel Slat Transparent Insulation Material for building energy conservation and daylight autonomy. Build Environ 2021;203:108048. https://doi.org/10.1016/J.BUILDENV.2021.108048.
[27] Nicoletti F, Kaliakatsos D, Ferraro V, Cucumo MA. Analysis of the energy and visual performance of a building with photochromic windows for a location in southern Italy. Build Environ 2022;224:109570. https://doi.org/10.1016/J.BUILDENV.2022.109570.
[28] Feng W, Zou L, Gao G, Wu G, Shen J, Li W. Gasochromic smart window: optical and thermal properties, energy simulation and feasibility analysis. Sol Energy Mater Sol Cell 2016;144:316–23. https://doi.org/10.1016/J.SOLMAT.2015.09.029.
[29] Mesloub A, Ghosh A, Kolsi L, Alshenaifi M. Polymer-Dispersed Liquid Crystal (PDLC) smart switchable windows for less-energy hungry buildings and visual comfort in hot desert climate. J Build Eng 2022;59:105101. https://doi.org/10.1016/J.JOBE.2022.105101.
[30] Fathi S, Kavoosi A. Effect of electrochromic windows on energy consumption of high-rise office buildings in different climate regions of Iran. Sol Energy 2021;223:132–49. https://doi.org/10.1016/J.SOLENER.2021.05.021.
[31] Papaefthimiou S, Syrrakou E, Yianoulis P. An alternative approach for the energy and environmental rating of advanced glazing: an electrochromic window case study. Energy Build 2009;41:17–26. https://doi.org/10.1016/j.enbuild.2008.07.008.
[32] Mesloub A, Ghosh A, Touahmia M, Albaqawy GA, Alsolami BM, Ahriz A. Assessment of the overall energy performance of an SPD smart window in a hot desert climate. Energy 2022;252:124073. https://doi.org/10.1016/J.ENERGY.2022.124073.
[33] Buratti C, Belloni E, Merli F, Zinzi M. Aerogel glazing systems for building applications: a review. Energy Build 2021;231:110587. https://doi.org/10.1016/J.ENBUILD.2020.110587.
[34] Ghosh A, Norton B, Duffy A. Measured thermal & daylight performance of an evacuated glazing using an outdoor test cell. Appl Energy 2016;177:196–203. https://doi.org/10.1016/J.APENERGY.2016.05.118.
[35] Ghosh A. Potential of building integrated and attached/applied photovoltaic (BIPV/BAPV) for adaptive less energy-hungry building's skin: a comprehensive review. J Clean Prod 2020;276:123343. https://doi.org/10.1016/J.JCLEPRO.2020.123343.
[36] Piffer Y, Lamberts R, Ordenes Mizgier M, Güths S. A review on windows incorporating water-based liquids. Sol Energy 2021;214:606–31. https://doi.org/10.1016/J.SOLENER.2020.11.072.
[37] Chutturi M, Gillela S, Yadav SM, Wibowo ES, Sihag K, Rangppa SM, et al. A comprehensive review of the synthesis strategies, properties, and applications of transparent wood as a renewable and sustainable resource. Sci Total Environ 2023;864:161067. https://doi.org/10.1016/J.SCITOTENV.2022.161067.
[38] McNeil A, Lee ES, Jonsson JC. Daylight performance of a microstructured prismatic window film in deep open plan offices. Build Environ 2017;113:280–97. https://doi.org/10.1016/J.BUILDENV.2016.07.019.
[39] Ihara T, Gao T, Grynning S, Jelle BP, Gustavsen A. Aerogel granulate glazing facades and their application potential from an energy saving perspective. Appl Energy 2015;142:179–91. https://doi.org/10.1016/J.APENERGY.2014.12.053.
[40] Fang Y, Arya F. Evacuated glazing with tempered glass. Sol Energy 2019;183:240–7. https://doi.org/10.1016/J.SOLENER.2019.03.021.
[41] Hemaida A, Ghosh A, Sundaram S, Mallick TK. Evaluation of thermal performance for a smart switchable adaptive polymer dispersed liquid crystal (PDLC) glazing. Sol Energy 2020;195:185–93. https://doi.org/10.1016/J.SOLENER.2019.11.024.
[42] Oh M, Lee C, Park J, Lee K, Tae S. Evaluation of energy and daylight performance of old office buildings in South Korea with curtain walls remodeled using polymer dispersed liquid crystal (PDLC) films. 2019. https://doi.org/10.3390/en12193679.
[43] Nabil A, Mardaljevic J. Useful daylight illuminances: a replacement for daylight factors. Energy Build 2006;38:905–13. https://doi.org/10.1016/J.ENBUILD.2006.03.013.
[44] Hemaida A, Ghosh A, Sundaram S, Mallick TK. Simulation study for a switchable adaptive polymer dispersed liquid crystal smart window for two climate zones (Riyadh and London). Energy Build 2021;251:111381. https://doi.org/10.1016/J.ENBUILD.2021.111381.
[45] Integrated Environmental Solutions. Reference data - Apache tables - table 6 thermal conductivity, specific heat capacity and density. Reference Data - Apache Tables; 2021. https://help.iesve.com/ve2021/table_6_thermal_conductivity_specific_heat_capacity_and_density.htm?ms. [Accessed 14 February 2023].
[46] Ghosh A, Mallick TK. Evaluation of colour properties due to switching behaviour of a PDLC glazing for adaptive building integration. Renew Energy 2018;120:126–33. https://doi.org/10.1016/j.renene.2017.12.094.
[47] LBNL. Optics | windows and daylighting. 2019. https://windows.lbl.gov/software/optics. [Accessed 14 February 2023].
[48] LBNL. IGDB. Data format | windows and daylighting. 2019. https://windows.lbl.gov/igdb-data-format. [Accessed 14 February 2023].
[49] NSG Group Pilkington. Pilkington Spacia^{TM} 2022. https://www.pilkington.com/en/global/products/product-categories/thermal-insulation/pilkington-spacia#overview. [Accessed 14 February 2023].
[50] OneBuilding.org. Europe-Region 6 2022, https://climate.onebuilding.org/. [Accessed 14 February 2023].
[51] YouGov. The YouGov Sleep Study. Part one - sleeping patterns | yougov. 2022. https://yougov.co.uk/topics/health/articles-reports/2022/06/29/yougov-sleep-study-part-one-sleeping-patterns. [Accessed 4 April 2023].
[52] Statista. Weekday wake up time in the UK in 2013. Statista; 2013. https://www.statista.com/statistics/269688/typical-weekday-wake-up-time-in-the-uk/. [Accessed 4 April 2023].
[53] ASHRAE, American National Standards Institute. Standard for the design of high-performance green buildings. 2020.
[54] Lawrence Berkeley National Laboratory. EnergyPlus^{TM} Input Output Reference 2021.
[55] Statista. Remote work in the UK. Statista; 2021.
[56] Autodesk Help: Glazing Properties for Illuminance Renderings n.d. https://help.autodesk.com/view/BUILDING_PERFORMANCE_ANALYSIS/ENU/?guid=GUID-5734F60C-2D58-4D61-B0E4-0FD336853A3D (accessed April 4, 2023).
[57] Buratti C, Belloni E, Merli F, Zinzi M. Aerogel glazing systems for building applications: a review. Energy Build 2021;231:110587. https://doi.org/10.1016/j.enbuild.2020.110587.
[58] Pilkington Pilkington. Spacia FAQ. 2012.
[59] Shaik S, Gorantla K, Venkata Ramana M, Mishra S, Kulkarni KS. Thermal and cost assessment of various polymer-dispersed liquid crystal film smart windows for energy efficient buildings. Constr Build Mater 2020;263:120155. https://doi.org/10.1016/J.CONBUILDMAT.2020.120155.
[60] Checkatrade. How much does window fitting cost in 2023?. 2023. Checkatrade, https://www.checkatrade.com/blog/cost-guides/window-fitting-cost/. [Accessed 16 April 2023].
[61] Garrido R, Silvestre JD, Flores-Colen I. Economic and energy life cycle assessment of aerogel-based thermal renders. J Clean Prod 2017;151:537–45. https://doi.org/10.1016/J.JCLEPRO.2017.02.194.
[62] McCarthy MUK. A Met Office review of the record-breaking summer in 2022 2022. https://www.preventionweb.net/news/met-office-review-uks-record-breaking-summer-2022. [Accessed 13 April 2023].
[63] Ofgem. Energy price cap explained | Ofgem 2023. https://www.ofgem.gov.uk/information-consumers/energy-advice-households/check-if-energy-price-cap-affects-you.