



Original Article

Experimental Evaluation of Passive Glazing Systems for Thermal Performance in Dubai's Hot-Arid Climate



Slefani Nada Salih Ammo, Md Azree Othuman Mydin* , Nooriaty Taib, Sharifah Fairuz Syed Fadzil

School of Housing, Building and Planning, Universiti Sains Malaysia, 11800, Penang, Malaysia

* Correspondence email: azree@usm.my

Abstract

The swift urban expansion of Dubai has resulted in the prevalent use of glass facades in skyscrapers, which, although visually attractive, present considerable difficulties regarding energy efficiency due to the region's harsh environment. This study investigated the thermal performance of various passive glazing configurations in Dubai, specifically evaluating double- (DGU), triple- (TGU), and quadruple-glazed (QGU) units. An experimental thermal glass chamber was constructed using a bottom-up methodology to facilitate the evaluation of three distinct glazing systems under severe summer meteorological conditions. Internal data loggers monitored air temperature and relative humidity to facilitate a comparative analysis of their thermal characteristics; concurrently, an external weather station documented the ambient microclimate to establish a baseline. The empirical findings demonstrated that the QGU consistently maintained lower interior air temperatures compared with other systems. Observational data and heat index measurements indicate that quadruple glazing significantly enhances indoor thermal comfort. The findings provide actionable recommendations for architects and engineers, highlighting the efficacy of sophisticated glazing solutions in mitigating the thermal problems encountered by contemporary architecture in Dubai's extreme climate. The study underscores the essential function of passive glass facades in realising ecologically efficient architectural solutions within urban environments.

Copyright © 2026 KARYA ILMU PUBLISHING - All rights reserved

Article Info

Received 16 April 2026

Received in revised form 11 September 2026

Accepted 20 September 2026

Available online 23 September 2026

Keywords

Dubai
Passive Glazing Systems
Low-E
Thermal Performance

1. Introduction

Glass constitutes the predominant construction material utilised in Dubai [1]. Double-glazed fenestration represents the industry standard, whereas triple-glazed systems are primarily allocated to healthcare facilities. Concurrently, quadruple-glazing systems are increasingly being integrated into public and commercial infrastructure, frequently in conjunction with vacuum glass innovations [2].

Current efforts emphasise identifying the optimal glazing strategy to mitigate the effects of Dubai's hot climate [3]. The present study hypothesises that the integration of an additional air cavity enhances thermal performance, thereby substantiating the premise that increased structural thickness correlates with superior outcomes. This paradigm, however, contravenes the use of passive vacuum glass. Consequently, considering anticipated power limitations, extensive inquiry is requisite to optimise energy regulation mechanisms [4]. This study assesses glazing performance in warm, humid climates to identify optimal alternatives for Dubai, as depicted in Figure 1. The primary objective of this research is to evaluate and optimise the implementation of passive glass facades in high-rise buildings within Dubai, with the aim of enhancing thermal efficiency without compromising essential aesthetic and functional requirements. Focusing on multi-pane configurations, the research simulates air cavities within multilayered glass systems to optimise thermal efficiency.

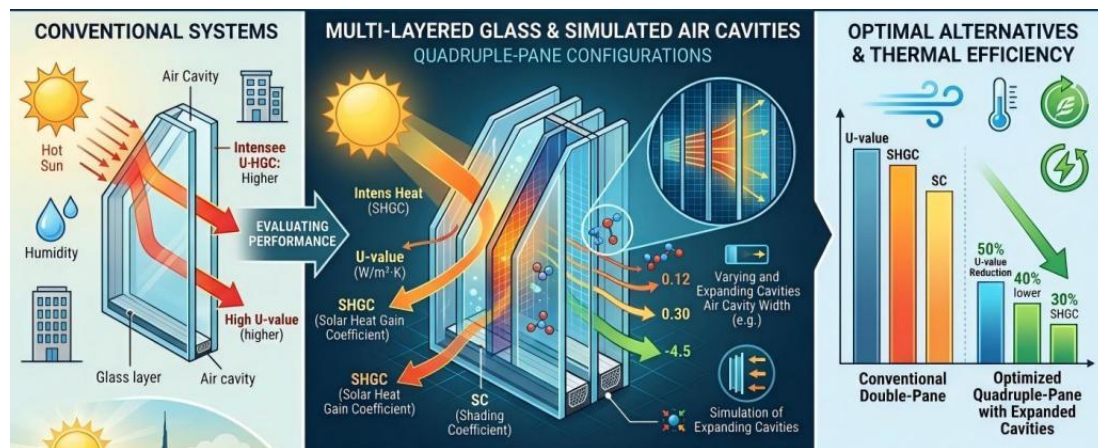


Figure 1. Objective of thermal efficiency.

Dubai possesses a hot, humid climate, thereby classifying it as a Zone B0 coastal city. As depicted in Figure 2 and referenced by the Dubai National Center of Meteorology (NCM), it presents a scorching desert environment. Its longest season, summer, experiences temperatures up to 50°C and humidity reaching 90%. As depicted in Figure 2, temperature peaks between May and late September. In contrast, humidity exhibits the opposite pattern, demonstrating that maximum temperatures invariably align with the lowest humidity levels.

Passive glazing technologies demonstrate the capacity to mitigate solar heat gain, enhance thermal resistance, and optimise internal environmental conditions. This investigation analyses various glazing systems to identify optimal configurations for Dubai's climate, utilising modelling and empirical data to assess facade thermal efficiency for energy-efficient temperature regulation.

2. Literature Review

To reduce carbon footprints and enhance the energy performance of structures with glass exteriors, stringent regulations have been implemented in Dubai. While the mandate for double-pane windows dates to the 1980s, contemporary glass systems now integrate three or four layers, providing superior thermal protection against severe weather conditions. Figure 3 illustrates visual examples of these glass structures in Dubai, highlighting various glazing typologies such as passive, active, and double-skin facades that are employed across both low-rise and high-rise constructions. In alignment with the Dubai 2040 Urban Master Plan, policymakers emphasise the unrestricted application of scientific innovations.

The development of a digital twin for Dubai is considered a critical objective by architects and engineers, solidifying the shift from conventional methodologies to the contemporary standard.

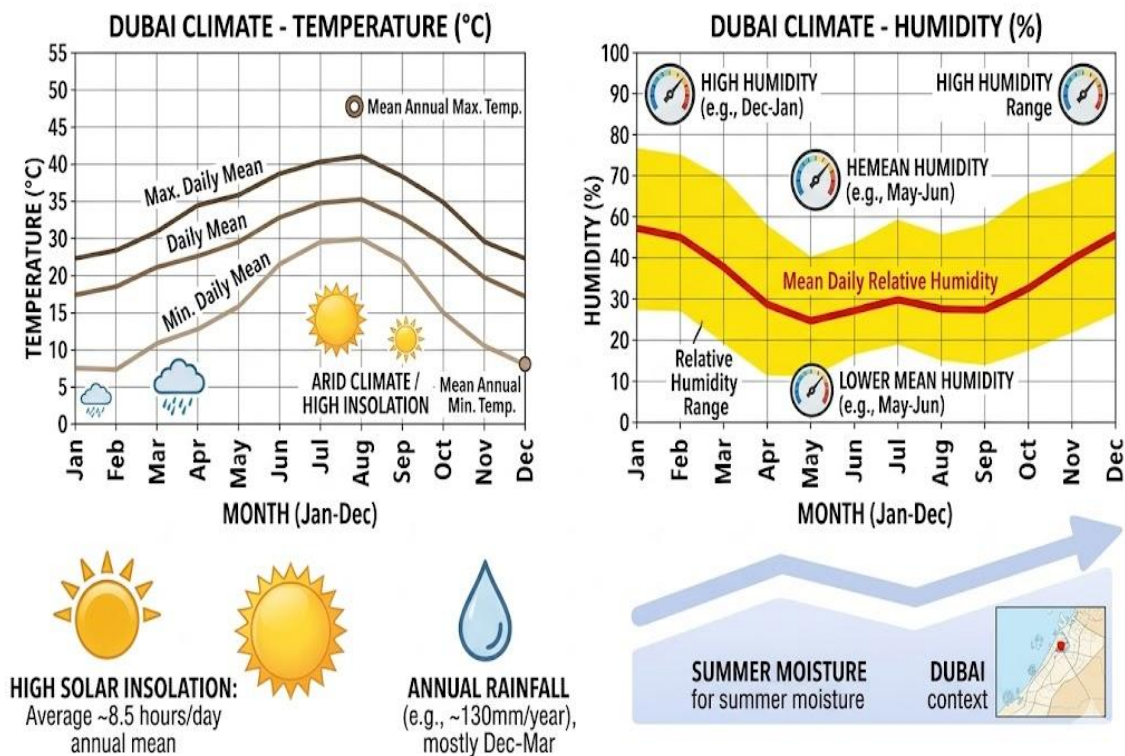


Figure 2. Air temperature and humidity (NCM).

The Burj Khalifa, recognised as the preeminent global skyscraper, exemplifies the zenith of contemporary engineering through its seamless integration of multifaceted glazing configurations within its architectural framework. The structural design utilises double, triple, or quadruple glass layers, contingent upon specific spatial requirements. The building's facade incorporates silver low-emissivity (low-E) glass, exhibiting a shading coefficient (SC) of 0.35. Figure 4 illustrates the glazing system of the Burj Khalifa, which was specifically engineered to accommodate the rapid urbanisation of Dubai.

Multi-pane window configurations, particularly quadruple-glazed systems, are preferentially utilised in the building envelopes of commercial structures due to their proven resilience against extreme thermal loads. These advanced materials integrate effectively with the modern fresh-air ventilation mechanisms conventionally embedded within the climate control infrastructures of high-rise buildings in Dubai. The application of these innovative glazing technologies is evident across diverse architectural typologies, ranging from the Emirates Towers (completed in 2000) to recent low-rise developments such as the 2022 MBRL Library, as well as the Al Maktoum International Airport (OMDW or DWC), which initiated phased operations in 2023 and is projected for full completion by 2050. Despite the municipality's relatively recent urban development, the systematic retrofitting and upgrading of existing architectural envelopes with advanced multi-layer glazing systems have been established as standard industry practices to enhance operational efficiency and overall performance metrics.

Figure 5 illustrates that recently constructed edifices in prominent locales—specifically the One Za'abeel twin towers and the helical Al Wasl tower—constitute crystalline skyscrapers. These structures exhibit a rigorously engineered configuration of double-, triple- and quadruple-glazed panels, explicitly

tailored to satisfy discrete project specifications. The architectural schematics delineates a streamlined, three-dimensional rectilinear framework integrated with vertical glass fins, which are designed to redirect aerodynamic flows. The upper elevations, incorporating double-skin facades, substantiate that a homogeneous glazing typology is inadequate for accommodating heterogeneous structural demands. The specification of glass and steel, predicated upon their structural integrity and adaptability within high-rise architecture, enables these edifices to effectively resist both seismic tremors and wind-induced lateral loads.

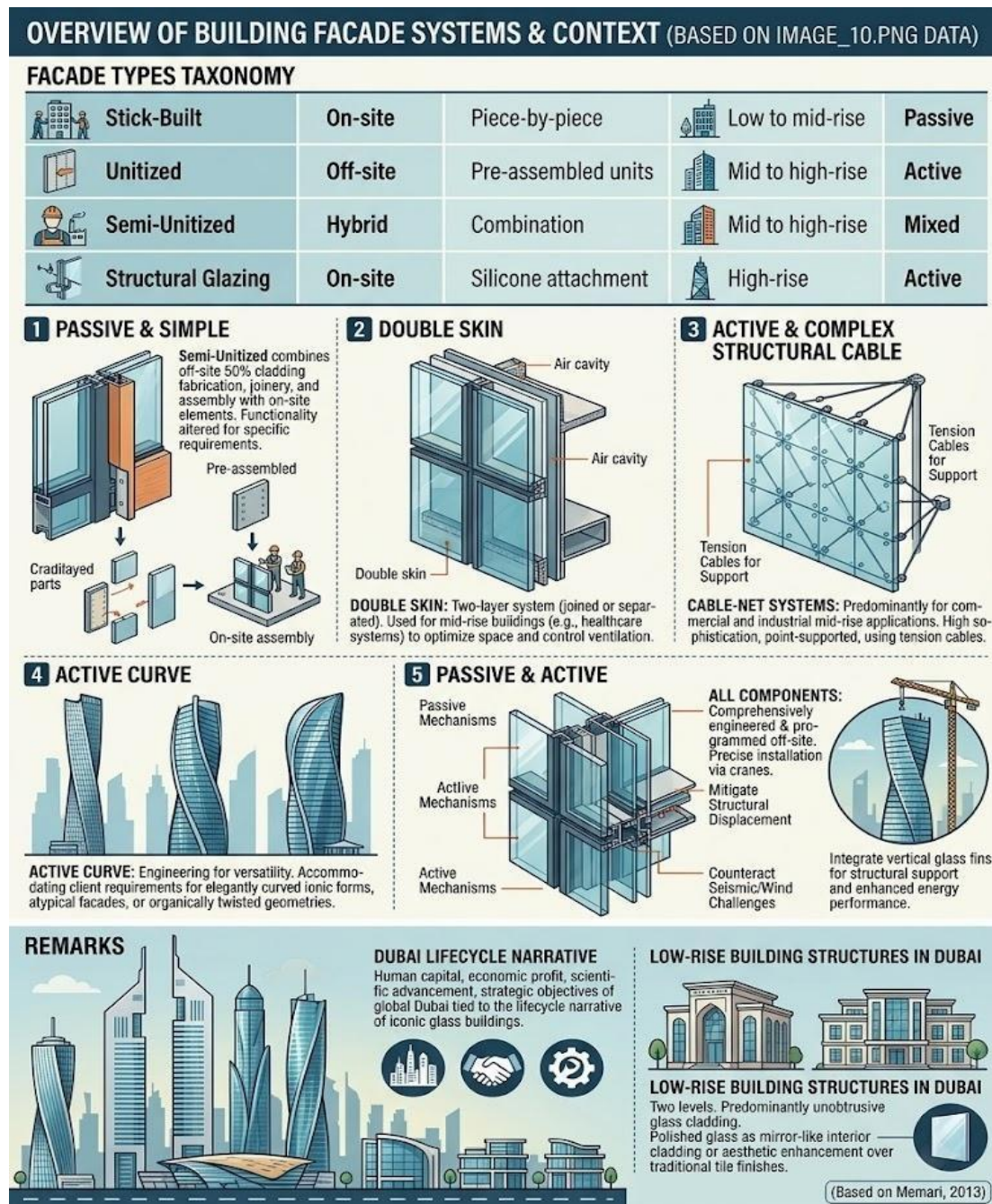


Figure 3. Types of glazing used in Dubai.

Glass systems deployed in Dubai comply with the established regulatory frameworks of both the United States (NFRC 300/200) and Europe (EN 410). Technological advancements in thin glass and lightweight framing have mitigated the weight of triple- and quadruple-glazed windows (NREL manual); consequently, their augmented performance currently justifies the associated costs, thereby facilitating their viable reintroduction [5]. Furthermore, ultra-clear glass is increasingly incorporated into these configurations for zero-energy building applications [6]. Bonham [7] posits that quadruple-glazed units augment energy efficiency via the integration of thin-film solar collection technologies. The examination of four-pane glazing configurations has become imperative, particularly given the incorporation of phase-change materials (PCM) between glass strata [8], which signifies an emerging trend in the adaptation of air-cooling mechanisms.

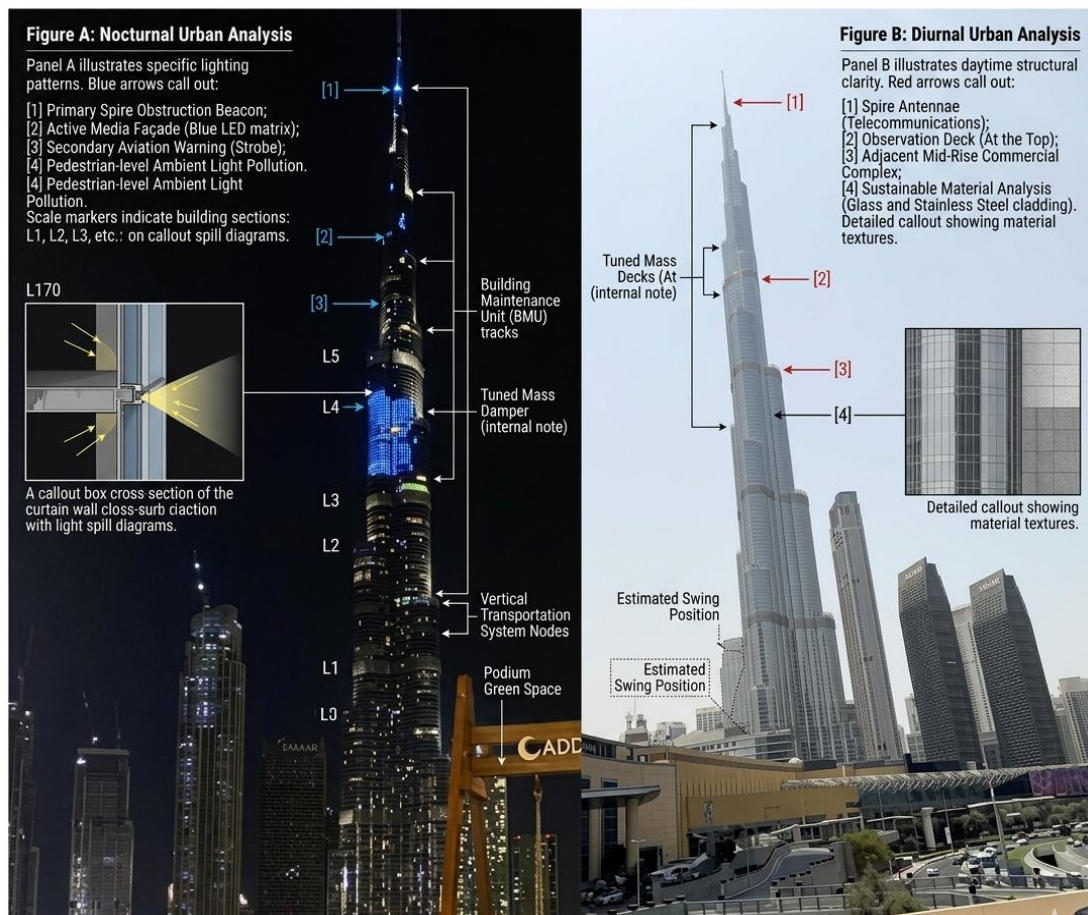


Figure 4. Glazing system of the Burj Khalifa.

These configurations substantially mitigate thermal gain. Furthermore, the incorporation of gas fillings enhances the durability of these systems, thereby rendering conventional solid walls increasingly obsolete in contemporary skyscrapers in Dubai. Nevertheless, a significant manufacturing concern stems from the degradation of air insulation under humid conditions, as moisture absorption demonstrably compromises its insulating efficacy. Compared to conventional designs, these four-pane passive windows demonstrate a 50% enhancement in thermal performance [9]. Both triple- and quadruple-glazed windows exhibit lower U-values relative to standard double-glazing systems [10].

A single glass pane exhibits a U-value of 5.4 W/m² K, whereas local double glazing achieves 2.1–2.5 W/m² K. Although insulating gases such as argon, krypton, and xenon enhance thermal efficiency,

their application remains infrequent. Typical air space widths range from 12 mm to 20 mm, although a width of 15–16 mm is considered optimal [11]. Gap dimensions vary depending on the gas type and the number of panes. Figure 6 delineates the optimal spacing as 14–15 mm for argon, 9–10 mm for krypton, and 6–7 mm for xenon [12–14]. Furthermore, Figure 6 illustrates optimal gap dimensions as a function of the gas type and presents various gap configurations appropriate for the climate of Dubai.

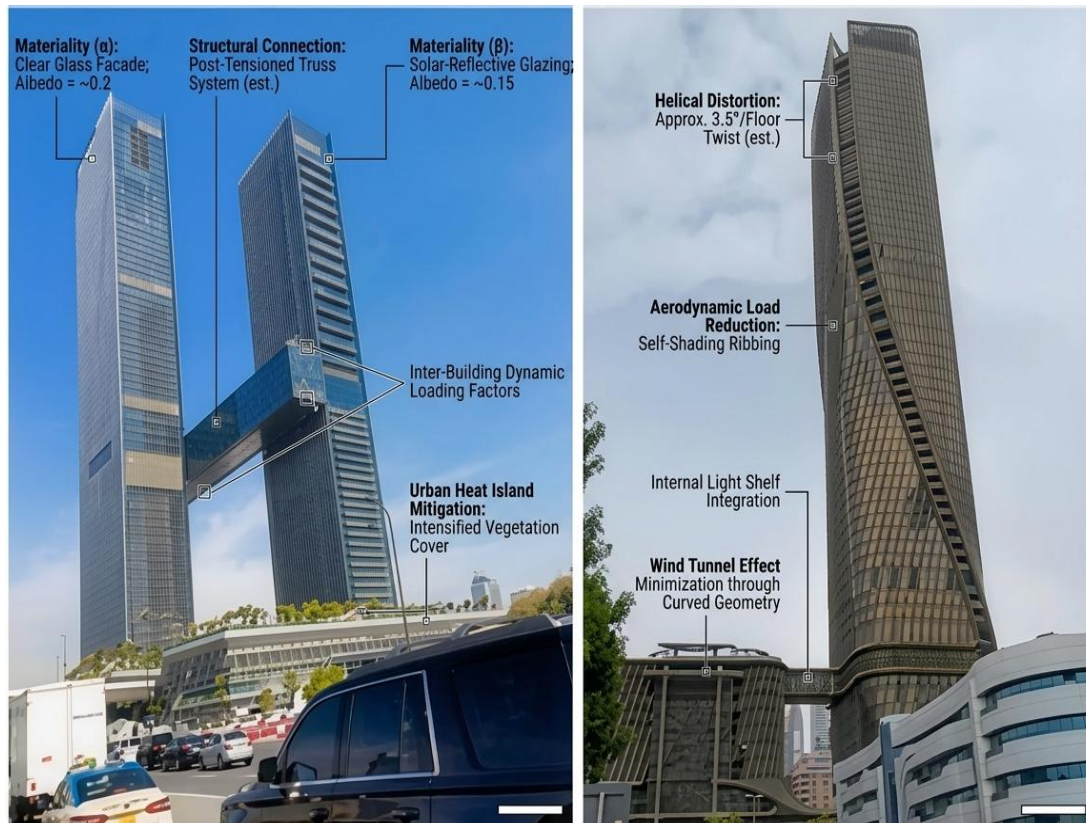


Figure 5. One Za'abeel (left) and Al WASL (right) buildings.

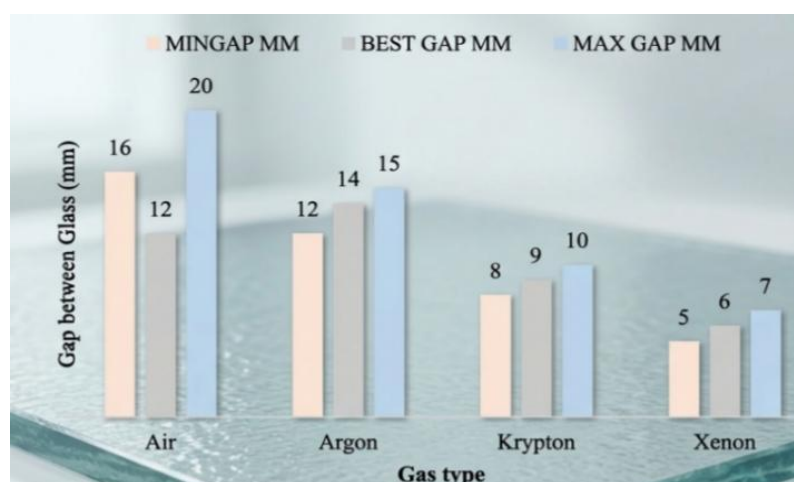


Figure 6. Gaps for the gas type.

A 12-mm air gap constitutes standard local practice and was adopted in this experimental study. This design incorporates natural air, thereby precluding the need for gas replenishments that require specialised maintenance protocols. Furthermore, the utilisation of natural air eliminates the necessity

for gas refills that demand specific maintenance. Conventional double-glazed units comprise an outer 6-mm low-emissivity glass pane, a 12-mm air cavity, and an inner 6-mm clear pane. For triple- and quadruple-glazed configurations, the spacing between the terminal layers is increased to 19–20 mm to accommodate reinforced framing [15].

3. Methodology

This research evaluates and optimises the thermal efficiency of glass facades in Dubai. It utilises experimental data to assess the influence of various glazing systems on energy efficiency and indoor thermal comfort, thereby providing insights into their operational performance. The experimental configuration strictly adheres to the NFRC 201 protocol and the Passive House methodology [16]. Furthermore, the bottom-up modelling approach for evaluating indoor comfort is preferred for energy analysis and the testing of material thermal efficiency.

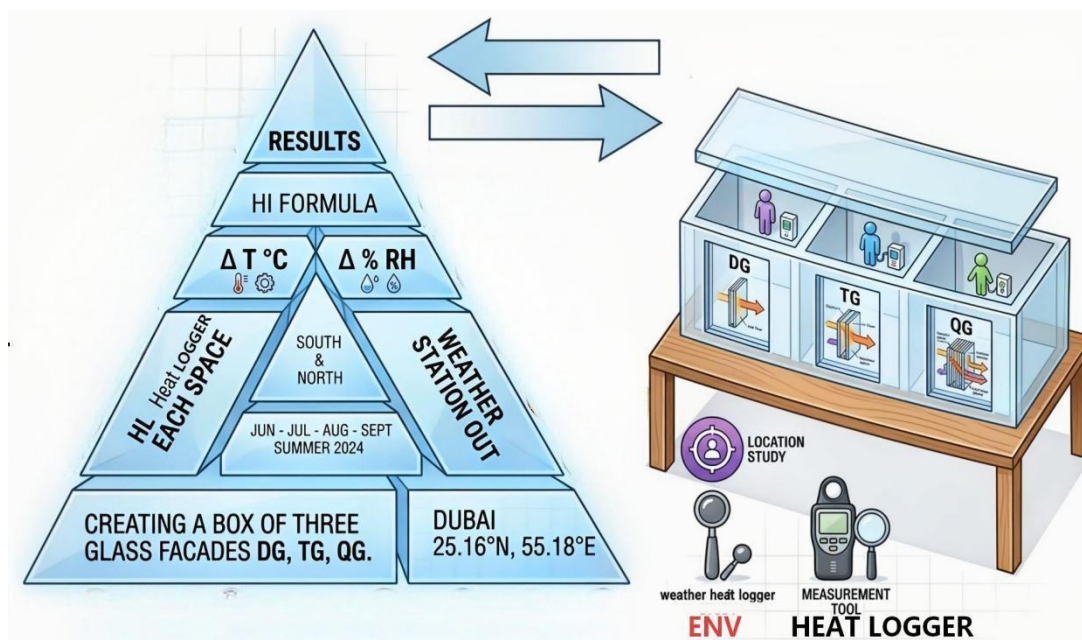


Figure 7. Simple box construction method.

As depicted at the base of the pyramid in Figure 7, an enclosure was constructed comprising three windows, each representing a specific glazing configuration: double glazing (DG), triple glazing (TG), and quadruple glazing (QG). The central section of the upper strata delineates the temporal scope of the study, spanning from June to September 2024. Adjacent to the pyramid, an ENV weather station functions as a thermal data logger for ambient air conditions. Concurrently, each internal compartment is equipped with an independent thermal logger to monitor the simulated indoor comfort conditions. The upper layers specify the primary variables of interest, namely temperature and relative humidity. Finally, the acquired data are processed utilising the heat index formula to ascertain the results.

3.1. Data Acquisition

Data collection was conducted using a custom-built experimental apparatus. This apparatus comprised a 170-cm Styrofoam chamber partitioned into three identical 50 × 50 × 50 cm compartments, as illustrated in Figure 8. Each compartment incorporated a distinct glazing configuration (DGU, TGU, or QGU), utilising 30 × 40 cm panels to maximise exposure while complying with regional opening ratio

regulations at the maximum floor-to-floor glazing height. Temperatures were monitored using internal and external data loggers. The experimental structure faced south from June to September 2024, covering full summer.

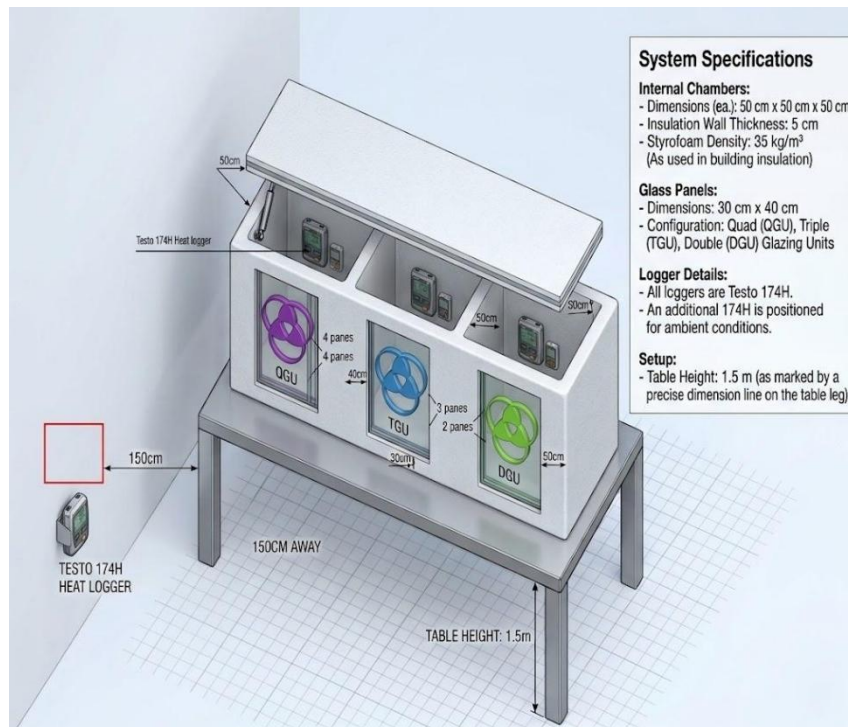


Figure 8. Glass box custom-built experimental apparatus.

As illustrated in [Figure 9](#), the polystyrene glass chamber featured frameless glazing affixed to its anterior facade, with the panes secured without the use of conventional framing. The glazing configuration comprised an exterior 6-mm tinted low-emissivity pane and 6-mm clear internal layers, separated by 12-mm air cavities. The apparatus was positioned in an unshaded environment, specifically mounted on a table adjacent to an unshaded construction site, and maintained a hermetically sealed condition throughout the experimental duration. As further depicted in [Figure 9](#), ventilation was intentionally precluded during the experimental protocols to ensure the sustained integrity of the hermetically sealed environment. The associated thermal imagery of the glass hot box designates A as the complete enclosure, B as the QGU, C as the TGU, and D as the DGU, which represents the most intensely heated unit.

3.2. Research Instruments and Tools

The primary equipment utilised comprised heat loggers (HL), specifically the Testo 174 model, alongside an interface device for data extraction. Custom software was procured from the manufacturer; despite the associated financial costs, its implementation ensured a high degree of accuracy. These instruments function as temperature regulation mechanisms within controlled laboratory environments, concurrently facilitating the localised enforcement of mandatory rest periods when thermal readings exceed a predetermined threshold of 50 °C. Data was recorded on an hourly basis by the loggers and subsequently extracted via the specialised software. As depicted in [Figure 10](#), this extraction procedure generates a Comma-Separated Values (CSV) file for each HL, categorised according to the specific type of facing glass. Hourly measurements were acquired by these instruments from 19 June to 30

September 2024. Subsequently, the data were transferred via the interface device and subjected to mathematical analysis, utilising the heat index in conjunction with various other formulas.

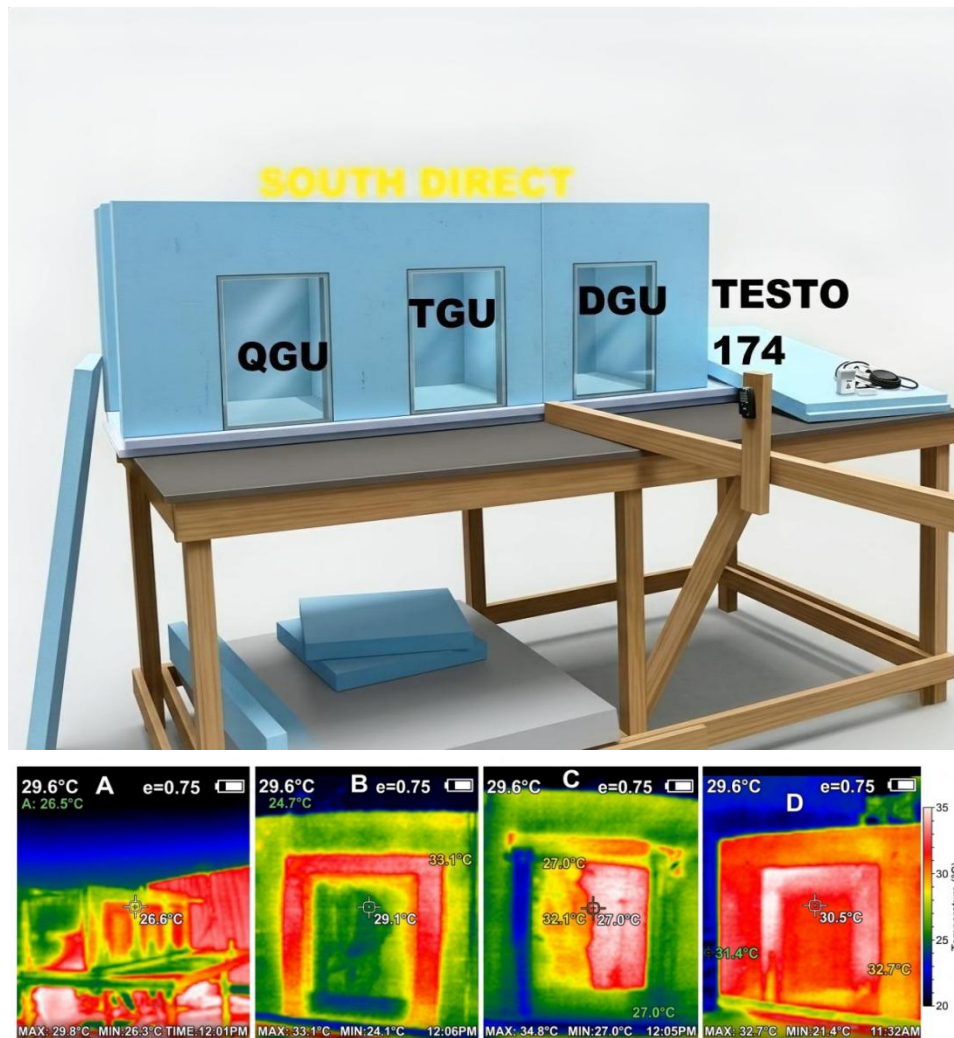


Figure 9. The glass hot box with thermal images: (a) represents the full box, (b) denotes the QGU, (c) indicates the TGU, and (d) corresponds to the DGU, which constitutes the most intensely heated unit.

3.3. The Glass Unit

In accordance with the manufacturer's specifications, the glass units were fabricated utilising 6-mm-thick glass to ensure compliance with regulatory standards. The U-value undergoes degradation during the summer months as a result of heat absorption, reaching a saturation point at levels approximately 10–15% lower. This phenomenon is applicable to both the frame and the air space (Cheng, R. et al., 2025). The exterior low-emissivity glass exhibited an external reflectance of 20% and an internal reflectance of 30%. Furthermore, it possessed a Solar Heat Gain Coefficient (SHGC) of 0.11, an initial U-value of 1.84 W/m² K that diminished to 1.7 W/m² K during summer, and a Shading Coefficient (SC) of 0.14. The interior panes demonstrated a reflectance of 36%, with the remaining parameters being comparable to those of standard clear glass.

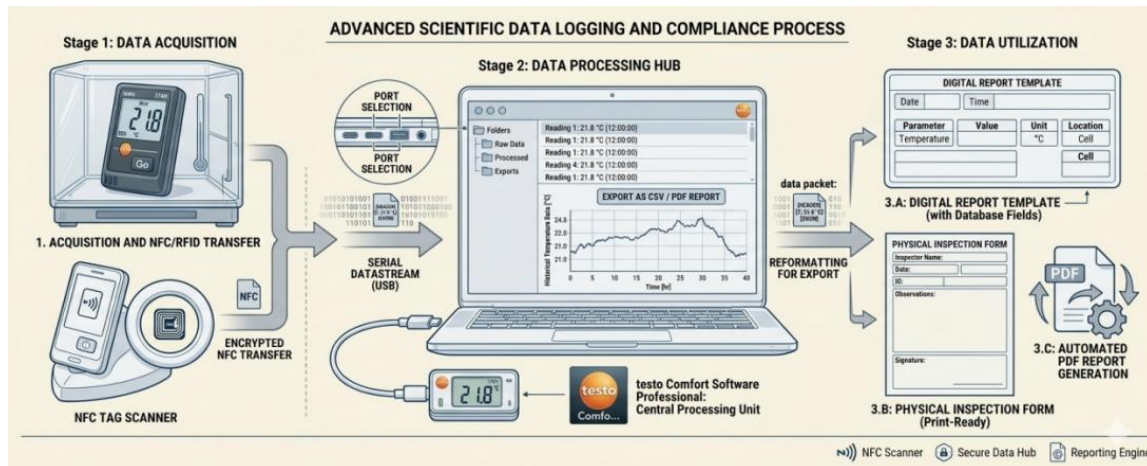


Figure 10. The (HL) data extraction process to a CSV file.

3.4. Data Analysis Formula

The heat index equation was employed to derive a specific numerical value through the integration of temperature and humidity [17]. Extensive data collection revealed distinct variations across multiple categories; therefore, the application of the heat index methodology was essential to validate the consolidation of temperature and humidity into a unified metric.

$$HI = C_1 + C_2 * T + C_3 * RH + C_4 * T * RH + C_6 * RH^2 + C_7 * T^2 * RH + C_8 * T * RH^2 + C_9 * T^2 * RH^2 \quad (1)$$

Equation (1) predicted the synergistic impact of temperature and humidity, which are critical determinants of indoor air quality, thereby influencing occupant satisfaction and comfort. Achieving optimal indoor PMV or PPD levels, without physical surveys, safeguards occupant health, well-being, comfort, and productivity. An equivalent volume of humidity and temperature data was recorded. These data were processed using various CSV file formats, including ENV, DGU, TGU, and QGU, and subsequently archived on GitHub.

4. Results

This section presents findings from field and prototype investigations assessing the thermal performance of glazing solutions in Dubai's high-rise buildings. This analysis elucidates the implications of these factors for energy consumption and thermal comfort, thereby underscoring the efficacy of passive glazing systems in mitigating solar heat gain and enhancing the overall indoor environmental quality.

4.1. Thermal performance of glass facades

Research demonstrates that it is crucial to assess indoor temperatures relative to the ambient environment, irrespective of the building's orientation. The experimental glass box was oriented towards the south, a direction generally regarded as suboptimal for the placement of fenestration during the summer months. Throughout the experiment, the glass enclosure remained completely sealed, even during inspections. Up until mid-September, it remained securely fastened in a southward-facing direction. The empirical data, collected from June through September 2024, encompasses more than 2000 discrete hourly measurements. The results indicate that the QGU provided the greatest thermal comfort and stability, as evidenced by minimal fluctuations in the temperature difference (ΔT). During

the day, its peak indoor temperature was 6–3°C cooler than the double-glazed unit and the triple-glazed unit.

During the nocturnal period, as depicted in Figure 11, temperatures across all glazing configurations exhibited substantial similarity, attributable to elevated internal humidity. These humidity levels remained consistently high across all units, albeit at a lower magnitude than the external ambient humidity. The mean indoor-outdoor temperature differentials (ΔT) were approximately +0.7 °C for the QGU, +0.9 °C for the TGU, and +1.6 °C for the DGU. In terms of thermal stability, the QGU exhibited performance comparable to that of the TGU. This phenomenon is attributed to the central positioning of the TGU, which is insulated by the air cavities formed by the DGU and QGU, as it benefits from fabrication limitations.

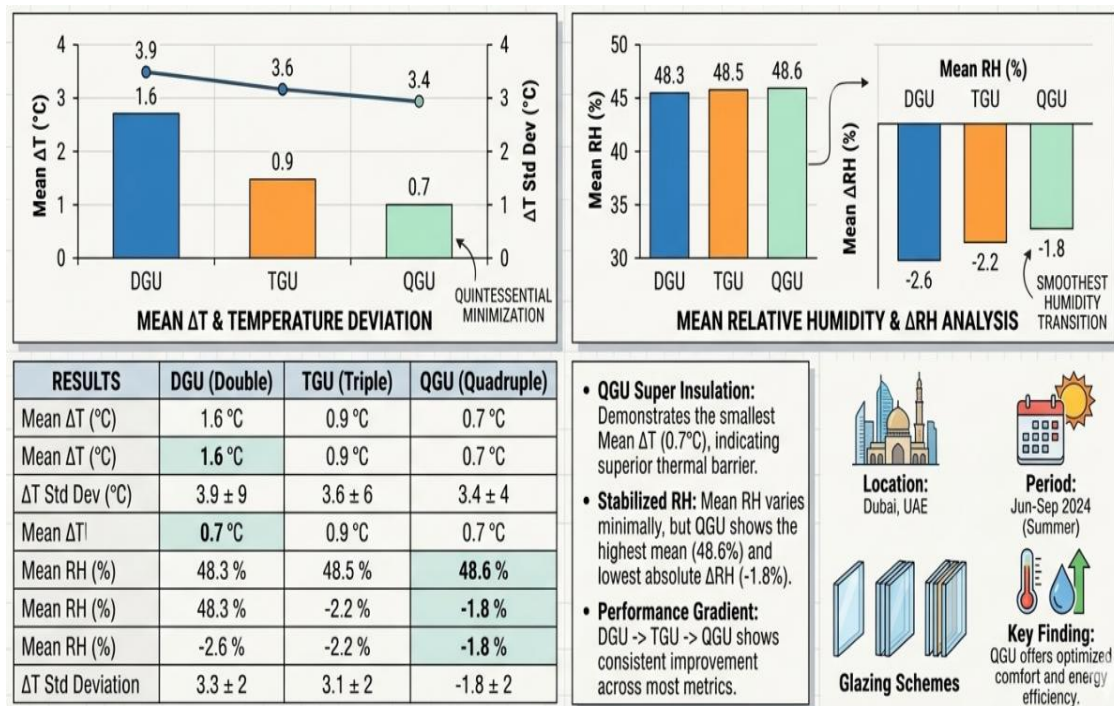


Figure 11. Results for the period from June–September 2024.

Despite this, the QGU ultimately delivers superior performance. Figure 11 displays detailed results, pointing to increased heat caused by strong solar radiation, along with the model's dimensions relative to its geographic site, orientation, and HL sensor location. The temporal and spatial constraints inherent in the experimental design rendered the recalibration and direct affixation of the HL loggers to the internal and external glass surfaces infeasible. As noted by multiple academic sources, the findings yield preliminary insights primarily concerning the U-value, rather than the Shading Coefficient (SC) or Solar Heat Gain Coefficient (SHGC) parameters, which typically necessitate iterative empirical validation.

4.2. Impact of Glazing Systems on Solar Heat Gain (SHGC)

In hot climates, including Dubai, a reduced Solar Heat Gain Coefficient (SHGC) is optimal for the mitigation of thermal gain. This metric is derived using the equation $SHGC = T + Q$, which integrates direct solar transmittance (T) and secondary heat transfer (Q). The US Department of Energy (DOE) and the National Fenestration Rating Council (NFRC) assert that the ideal SHGC—a parameter

quantifying the transmission of solar radiation through glazing systems for warm climates generally resides within the range of 0.2 to 0.4, as presented in [Table 1](#). This range establishes an effective equilibrium between the reduction of thermal loads and the provision of adequate natural illumination.

Table 1. SC and SHGC for Different Glazing Types.

Glass Type	SC = SHGC/0.87	SHGC or G-value = T+Q
Clear single-glazed	1.0	0.87 (high heat gain) for cold climates
Low-E glass single	0.3 - 0.5	0.2-0.4
Reflective glass	0.2 - 0.4	0.2–0.3 rare metal treated (Hu et al., 2020)
Double glazing (DGU)	0.5-0.68	0.5–0.6 for moderate climates
Triple glazing (TGU)	0.3 - 0.55	0.2 - 0.4 for hot climates
Quadruple glazing (QGU)	0.15 - 0.35	0.15 - 0.3 0.15 - 0.3 for hot climates

The shading coefficient (SC) is derived from the Solar Heat Gain Coefficient (SHGC) via the equation $SC = SHGC / 0.87$, as presented in [Table 1](#). This parameter serves as an indicator of solar heat mitigation, with lower values denoting superior thermal management. Consequently, this metric is predominantly utilised in Dubai for thermal load calculations. In accordance with ASHRAE standards, SC values range from 0 to 1. An SC value of 1 indicates that the window's solar heat transmission is equivalent to that of standard clear single glazing. Furthermore, [Figure 12](#) provides a comparative analysis of the SHGC across various glazing typologies, specifically encompassing the previously referenced Double Glazed Unit (DGU), Triple Glazed Unit (TGU), and Quadruple Glazed Unit (QGU) employed in the empirical investigation.

When the solar coefficient (SC) is below 0.35–0.5, the window transmits less solar heat, thereby contributing to the reduction of cooling loads in hot climates [\[18\]](#). Conversely, an SC value exceeding 0.5 indicates a higher transmission of solar heat, a characteristic comparable to that of standard clear glass. This characteristic is undesirable in elevated temperature environments, potentially resulting in heightened cooling demands.

The incorporation of rare metals into glass significantly attenuates the absorption of solar thermal radiation. By obstructing infrared radiation while preserving visible light transmittance, this material mitigates reliance on air conditioning systems. Consequently, the implementation of this glass in hot climates enhances indoor thermal comfort and diminishes cooling-related energy consumption. Nevertheless, its application remains primarily restricted to the research and development phase due to prohibitive costs and supply constraints [\[19\]](#).

The selection of window typologies and materials, particularly high-efficiency low-emissivity (low-E) glazing, significantly attenuates solar heat gain while optimising natural light transmittance [\[20\]](#). Furthermore, the strategic integration of shading mechanisms and optimal building orientation maximises daylight penetration and minimises direct solar irradiance, thereby enhancing energy efficiency and promoting sustainable architectural paradigms in Dubai. [Table 1](#) presents the SC and SHGC, categorised according to glazing type and prevailing climatic conditions. This delineation underscores that the specification of appropriate coatings is critical for achieving an optimal equilibrium between maximising natural illumination and ensuring effective thermal management [\[12–14\]](#). The data presented in this table are derived from W7.4 and supplementary digital resources.

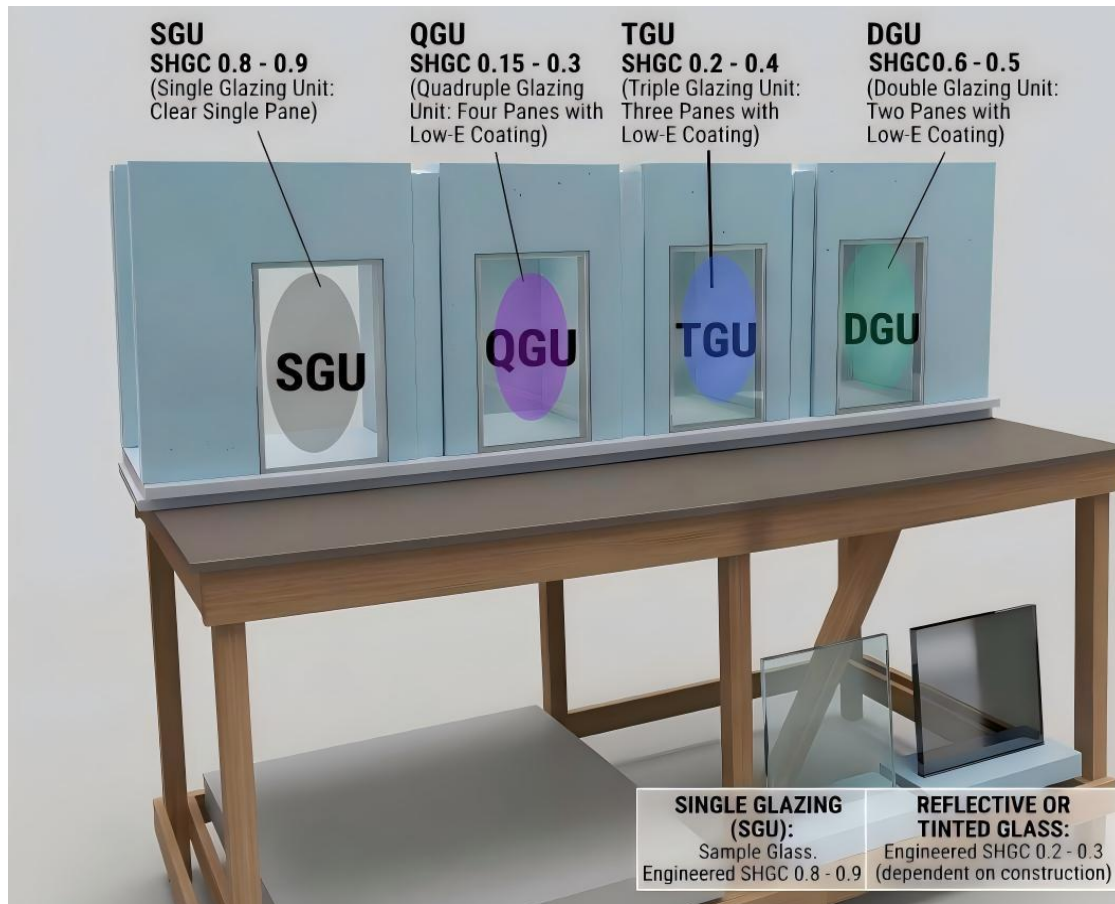


Figure 12. A comparison of the SHGC across several glass types.

The glass box experiment showed that the multi-layered Low-E glazing system performed better than double-glazed configurations at mitigating solar heat gain. This reduction consequently led to a decrease in interior temperatures, thereby diminishing reliance on mechanical cooling and enhancing thermal comfort. The architect is responsible for determining the colour and thickness of the coating, which includes selecting the application surface, whether interior or exterior. Through the systematic evaluation of diverse combinations, the required specifications are achievable.

4.3. Effect on Indoor Thermal Comfort

In accordance with local manufacturing protocols, the exterior layer of the glass envelope was fabricated from low-emissivity glass, whereas the internal layers consisted of conventional transparent glass. Table 2 details the application of low-emissivity glass and its subsequent effects on the relevant parameters. Instead of utilising specialised insulating gases, the units were filled with ambient air, maintaining a uniform 12-mm cavity to ensure adherence to current low-emissivity (low-E) fenestration standards [21]. As illustrated in Figure 13, which presents various configurations combining low-E coatings with multi-pane glazing, the integration of low-E glass improves the U-value and correspondingly increases the thermal resistance (R) ($U = 1/R$). Furthermore, empirical evidence demonstrates that low-E coatings effectively mitigate external glare while sustaining adequate indoor visible light transmission (VLT) levels. Additionally, the application of this coating can reduce the total heat flux by up to 34%, thereby increasing the thermal resistance from $0.50 \text{ m}^2\cdot\text{K}/\text{W}$ in uncoated configurations to $0.632 \text{ m}^2\cdot\text{K}/\text{W}$ in their coated counterparts [22].

Table 2. Low-emissivity (low-E).

Quadruple glass (6) + air (A) 12 mm	Low-E scenario	R-value calculated = 1/U
6-A-6-A-6-A-6	No low-E	2.532
6-A-6-A-6-A-6	One low-E	3.157
6-A-6-A-6-A-6	Two low-E	3.8782

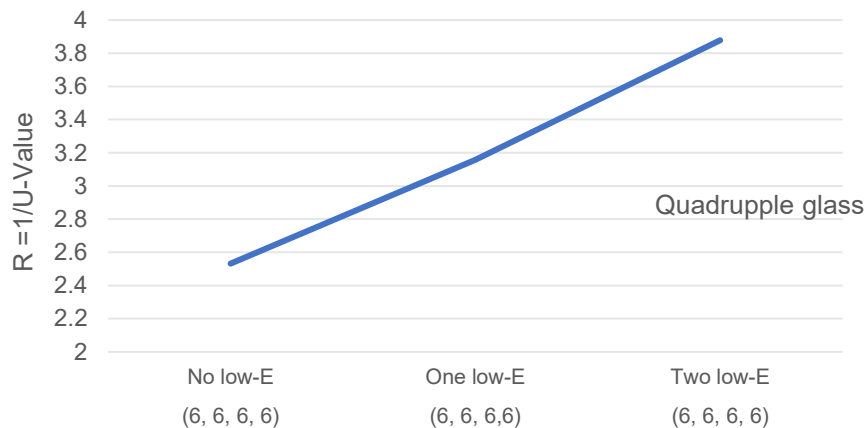


Figure 13. R-value increasing with Low-E ($U = 1/R$).

Glass variables were evaluated per Dubai's building regulations, not laboratory certifications. To mitigate cooling demands in Dubai, the shading coefficient (SC) is maintained at a value not exceeding 0.4. This parameter is considered optimal for high-rise structures, as their architectural designs typically preclude the integration of alternative shading mechanisms. During the experimental phase, a frameless configuration was employed to preclude a 30–40% diminution in energy efficiency. This method simulated smart window technologies that regulate light and solar heat, enhancing indoor comfort. These systems exhibit dynamic adaptation to meteorological conditions, subsequently reducing dependence on artificial lighting and heating, ventilation, and air conditioning (HVAC) systems, which contribute to energy conservation [23].

Advanced systems employ rare metals and polymers to mitigate thermal bridging; however, achieving U-values as low as $0.8 \text{ W/m}^2\cdot\text{K}$ remains an ongoing developmental objective [24]. Architects frequently prioritise minimal or concealed framing structures. Although the utilisation of UPVC or timber facilitates high-quality installations, these materials are associated with higher financial implications [25]. The glass chamber establishes the U-value of the QGU, as delineated in Table 3, demonstrating thermal performance commensurate with that of an opaque wall at $0.4 \text{ m}^2\cdot\text{K/W}$. Furthermore, uninsulated walls exhibit inferior U-values in comparison to triple-glazed systems [26].

With regard to temperature and humidity, the principal observation is that all glazing configurations exhibit elevated temperatures relative to the external environment (ENV), which serves as the outdoor weather station, alternatively designated as the outer HL. Between 6:00 AM and 8:00 PM, the mean temperature increment for double-glazed units (DGU) exceeds $+2.9^\circ\text{C}$. Conversely, triple-glazed units (TGU) demonstrate an increase of approximately $+2.1^\circ\text{C}$, whereas quadruple-glazed units (QGU) record the minimum elevation of $+1.8^\circ\text{C}$. During nocturnal periods, all evaluated units display enhanced thermal insulation properties.

Table 3. Glass variable of glass chamber.

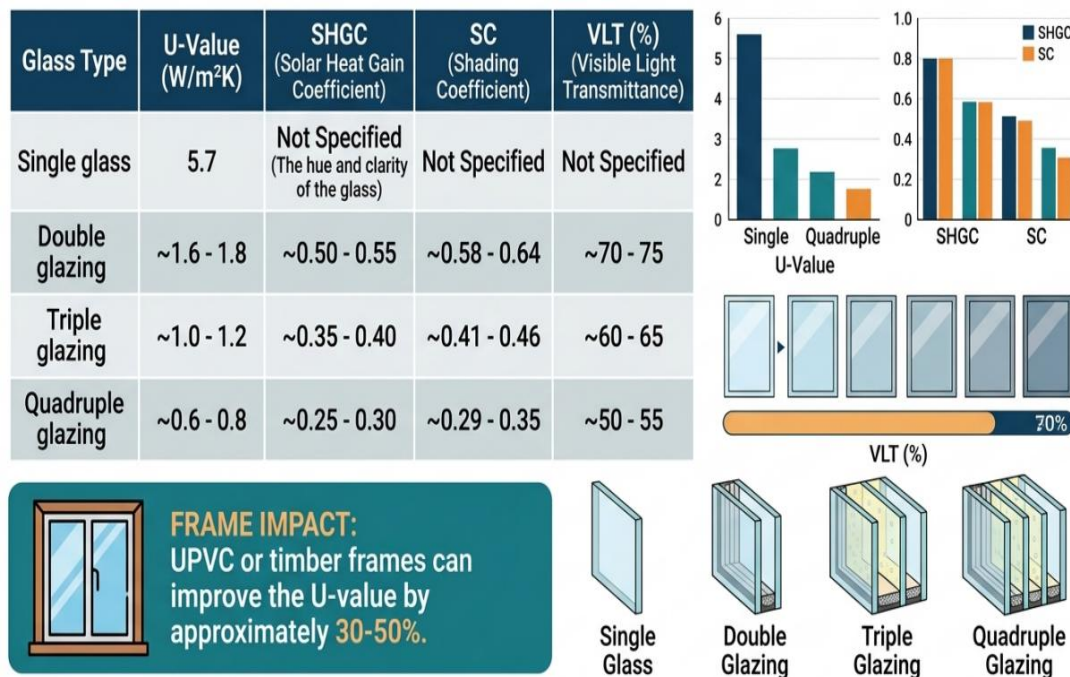


Figure 14 illustrates that the QGU exhibits superior thermal efficiency during diurnal periods compared to alternative systems, although its performance diminishes nocturnally. Correspondingly, the peak temperatures for the TGU and DGU are recorded at 58°C and 60°C, respectively. Following the conclusion of the summer season, the performance of the QGU, TGU, and DGU demonstrates a more pronounced dependence on (SHGC) than on the U-value. This phenomenon is attributed to the solar trajectory and latitudinal positioning. Specifically, at 14:00, the QGU registers a temperature of 59.0°C, in contrast to the ENV's recorded outdoor mean temperature of 51.00°C. Concurrently, the mean temperature of the TGU is 60.0°C, while the peak mean temperature of the DGU attains 61.0°C. Further analysis indicates that the maximum temperature of the QGU escalates to 57°C, as opposed to 50°C for the ENV.

Similarly, the peak temperatures for the TGU and DGU are recorded at 58 °C and 60 °C, respectively. During nocturnal periods, minimum temperatures are observed, with both the QGU and TGU fluctuating between 0.1 °C and 0.2 °C. Relative to the ENV, the DGU exhibits a marginally elevated minimum temperature of 0.4 °C. Observational data indicate that the QGU is advantageous owing to its highly stable temperature profile, which is characterised by reduced acute fluctuations and a more consistent thermal transition.

The TGU demonstrates a balanced performance, exhibiting moderate thermal elevations. Conversely, the DGU displays the most pronounced diurnal temperature increase, characterised by intensive solar heat absorption and significant thermal variability. Furthermore, consistent humidity levels are maintained across the QGU, TGU, and DGU. During diurnal hours (06:00 to 16:00), a pronounced greenhouse effect is observable across all glazing configurations, as illustrated in Figure 15. The most substantial temperature elevation occurs between 10:00 (10 AM) and 16:00 (4 PM), concurrent with a reduction in relative humidity (RH) levels. Conversely, during nocturnal hours (18:00 (6 PM) to 07:00 AM), as RH levels increase, all glazing variants provide marginal insulating benefits that are modulated by ambient atmospheric moisture.

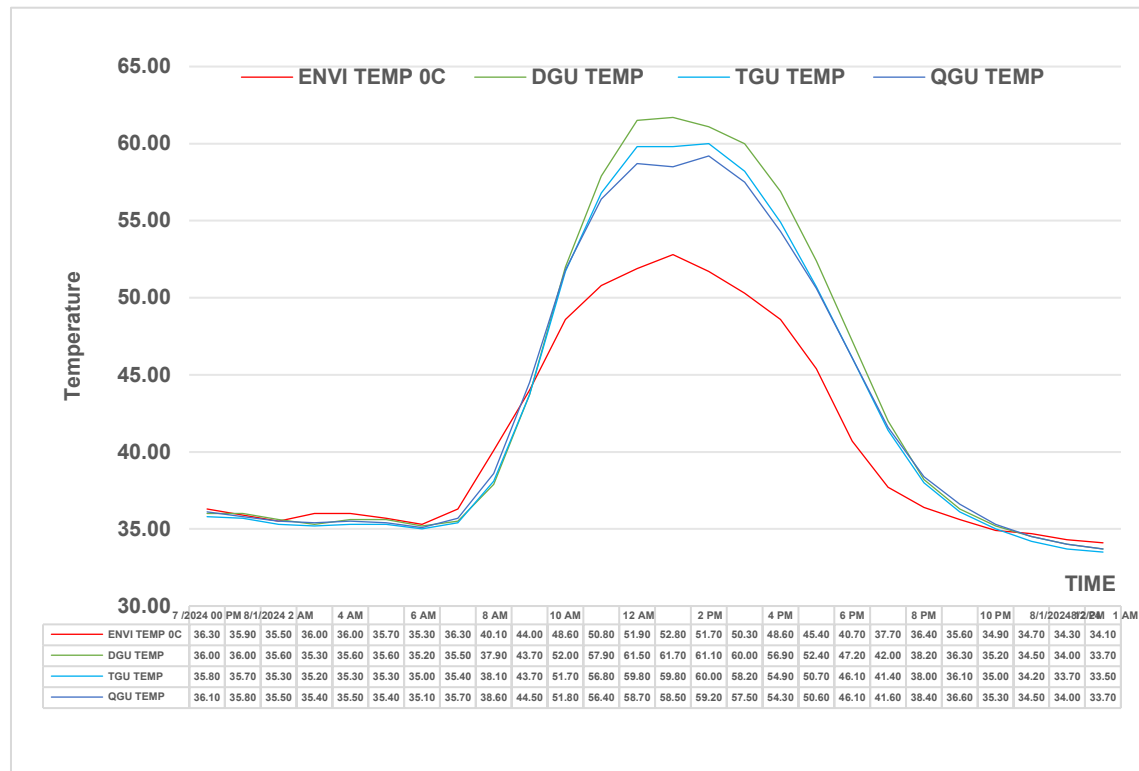


Figure 14. Indoor temperature in Dubai for one day.

Following fluctuations in external ambient temperatures, a thermal lag of one to two hours remains evident. In this context, QGU demonstrates superior energy efficiency regarding thermal enhancement and the modulation of temperature fluctuations. Consequently, QGU emerges as the optimal glazing alternative, aligning with the climate control objectives of Dubai by effectively balancing thermal consistency and maximum solar heat gain. Although the current study primarily focuses on the summer season, 1 August was specifically selected to represent peak thermal conditions. During this period, the glass models were evaluated in a south-facing orientation, which constitutes the most severe configuration. Given that the calculated heat and humidity levels reached their maximum, the heat index formula was applied; the corresponding results are illustrated in [Figure 16](#).

All recorded temperatures were converted to Fahrenheit prior to analysis, as the derivation of the heat index necessitates this unit rather than Celsius. The results demonstrated variations in the heat index, suggesting limited practical applicability attributable to the compact dimensions of the experimental prototypes; specifically, the incorporation of an additional layer produced marginal differences in the heat index. This outcome is attributed to the scale of the experimental model, the restricted duration of the study, and the precision of the measurement instrumentation, all of which constitute factors that influenced the observed relative differences among the respective glazing materials.

Consequently, the application of a correction factor is recommended to ensure data accuracy [27]. The incorporation of an additional glass pane with an air cavity layer improved the indoor heat index by approximately 10%. Experimental trials indicated an 8°C variance in peak midday temperatures. At a maximum outdoor temperature of 66°C, the quadruple glazing demonstrated significantly superior thermal performance, reaching 74°C, in contrast to 77°C for double glazing and 76°C for triple glazing. Conversely, as illustrated in [Figure 12](#), the effect of humidity reduced nocturnal temperature differentials to 0.1°C across all glazing configurations.

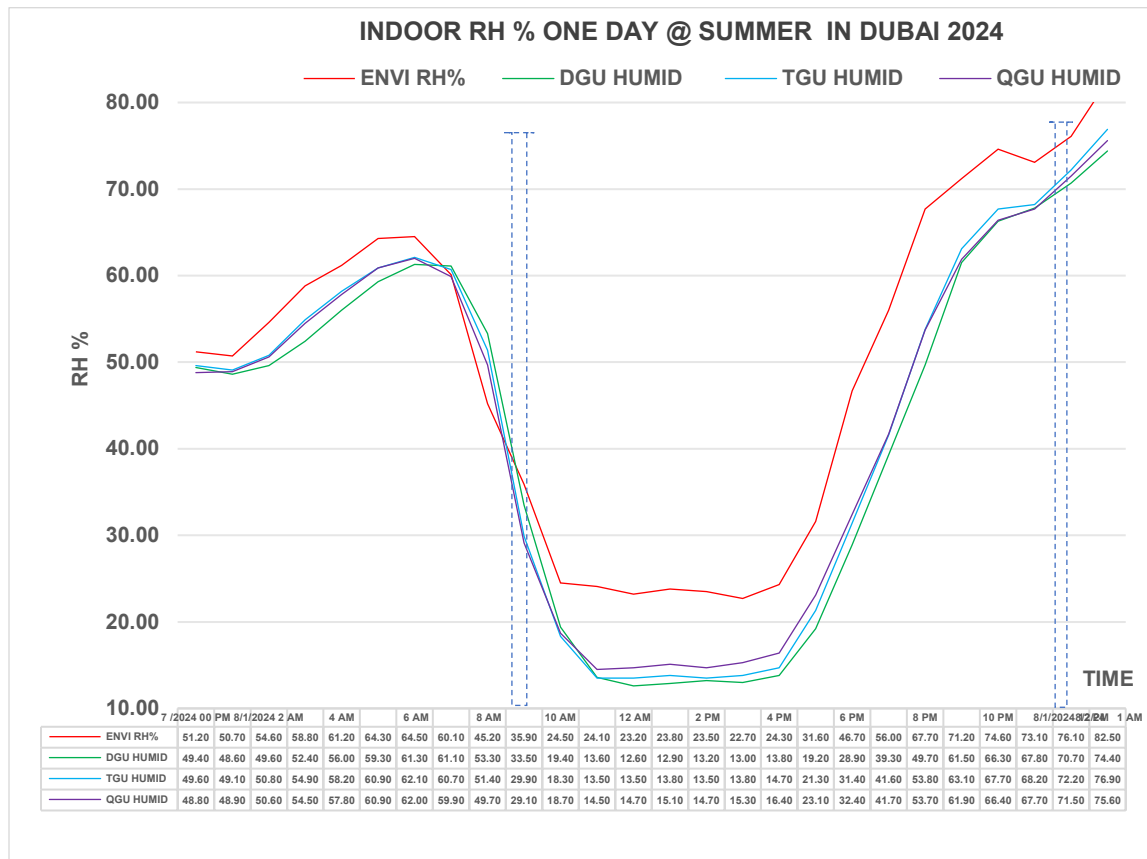


Figure 15. Reduction in relative humidity (RH) beginning at 10:00 AM and continuing until 4:00 PM.

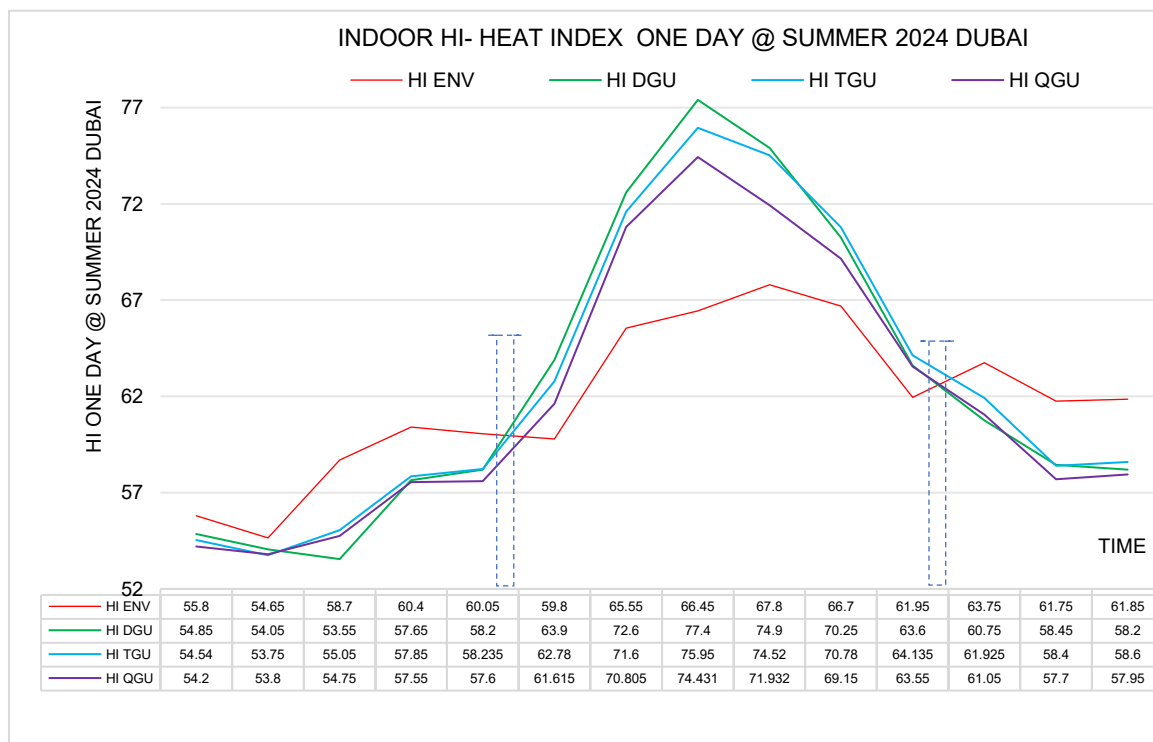


Figure 16. Indoor of QGU aligns with the outdoor external ENV.

Nevertheless, the observed values exhibited fluctuations ranging from 2°C to 8°C. Although these findings are promising, they underscore the necessity for an extended evaluation period of approximately one year, consistent with the recommendations of Spanish researchers [27]. The columns presented in Figure 12 indicate that the data acquired from the quadruple and alternative glazing configurations demonstrate a close alignment with the external environmental temperatures recorded by the thermal logger. A marginal discrepancy of 1°C to 2°C was observed at the time of data collection, as evidenced by the intersection where all values converge at 06:00 and midnight.

4.4. Energy Consumption and Cooling Load Reduction

Drawing upon empirical data collected during the summer period in Dubai, a comparative analysis was conducted to assess the cooling load efficiency of double-, triple-, and quadruple-glazing systems. To ensure methodological consistency, all outcomes were normalised per square metre of the glazed surface area, with rigorous consideration given to the respective U-values. Table 4 shows the estimation of annual conductive heat transfer through glazing (W).

The annual conductive heat transfer (Wh) through the glazing is estimated by employing 2,508 cooling degree days (CDD) at a base temperature of 23°C, consistent with the economic recommendations established by authorities in Dubai (Salem et al. 2022). The computation of (Wh) is determined by the following equation:

$$(Wh) = U_w (W/m^2 \cdot K) \times \text{Area} (m^2) \times CDD (^\circ C \cdot \text{day}) \times 24 (h/\text{day})$$

This value is subsequently divided by 1,000, thereby incorporating a coefficient of performance (COP) of 3 kW, which is characteristic of split-unit air conditioning systems [9]. Fundamental air conditioning calculations, using 0.3–0.58 W/m²·K for QGU and TGU, indicate that quadruple glazing (QGU) reduces the required cooling load to approximately 40%, as Table 4 illustrates.

4.5. Discussion and Implications for Future Design

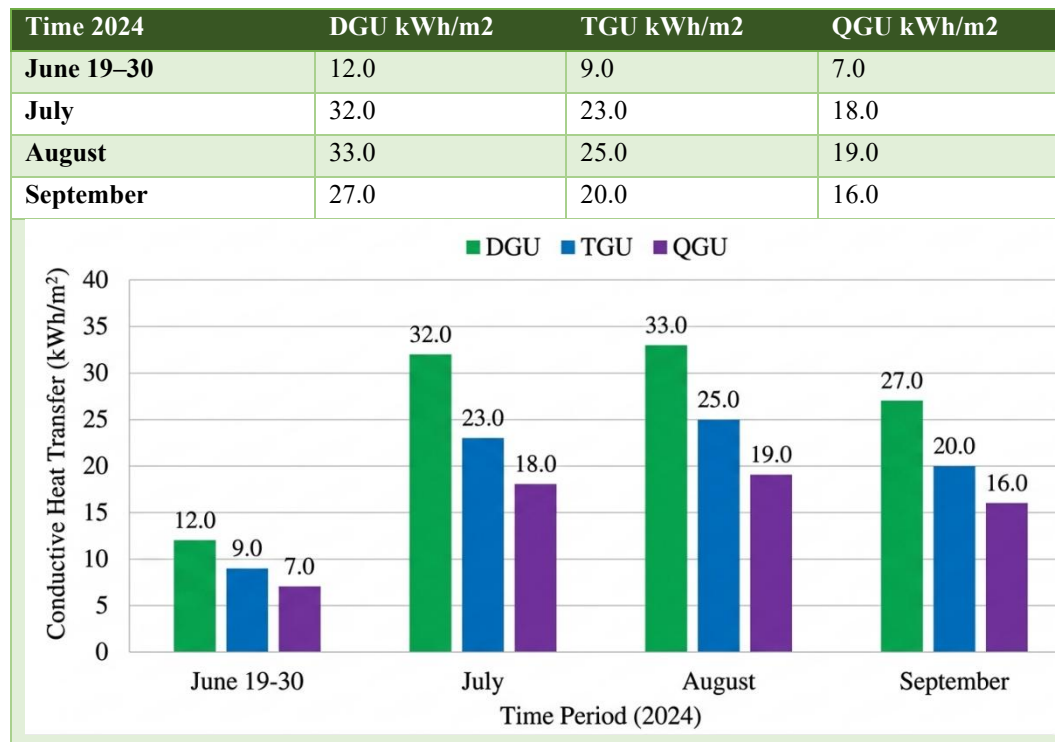
Due to the extensive initial deployment of double-glazed systems in Dubai, a critical necessity has emerged to execute comprehensive upgrades and retrofitting procedures for these glass facades utilising advanced technological frameworks. This modernisation is imperative to ensure compatibility with recently integrated sustainable cooling systems. The practical implementation of these retrofits systematically augments operational efficacy.

Future designs should incorporate multi-layered glazing with low-emissivity (low-E) coatings to maximise thermal resistance and reduce heat transfer by up to 34%. Furthermore, quadruple-pane configurations enable the strategic integration of such systems with phase-change materials (PCMs) encapsulated between the glazing layers, thereby establishing an emerging trajectory in contemporary cooling methodologies.

Furthermore, the incorporation of thin-film solar-harvesting technologies into quadruple-glazed units (QGU) provides a direct mechanism for augmenting the comprehensive energy performance of buildings. Furthermore, QGU deployment functions as an advanced thermal barrier, capable of maintaining peak daytime indoor temperatures 6–8°C below those observed with double-glazed (DGU) systems, and correspondingly lower than triple-glazed (TGU) configurations.

To ensure structural integrity against wind and seismic forces, contemporary multi-skin glass facade designs incorporate building envelope components, such as vertical glass panels, to alter aerodynamic wind patterns. This approach applies to tall buildings because towers typically lack external shading and must maintain a Shading Coefficient (SC) of 0.4 or less to reduce cooling loads.

Table 4. Estimation of Annual Conductive Heat Transfer Through Glazing (W).



5. Conclusion

The following conclusions can be drawn from the present study:

1. **Material Synergies:** The efficacy of these multi-layered configurations is substantially augmented through the integration of low-emissivity (low-E) coatings. These coatings serve to mitigate solar heat gain and improve thermal insulation while preserving visible light transmittance.
2. **Efficiency in Energy and Cooling:** The strategic integration of advanced quadruple-glazed fenestration systems significantly curtails mechanical cooling requirements by an impressive margin of approximately 40%. This innovative architectural approach mitigates solar heat gain and enhances thermal insulation, considerably lessening the operational burden on internal HVAC systems. This provides a substantial, long-term benefit for energy management and sustainability in modern high-rise structures.
3. **Superior Thermal Efficiency:** Quadruple Glazed Units (QGU) outperform both Double-Glazed Units (DGU) and Triple Glazed Units (TGU), facilitating optimal indoor thermal comfort and climate stability. Thus, they emerge as the preeminent solution for Dubai's hyper-arid, elevated-temperature environment.
4. **Thermal Stability:** Throughout the day, QGUs show minimal temperature fluctuations and gradual thermal transitions, attenuating severe temperature variations typical of conventional double-glazed windows.
5. **Future Verification:** Although QGUs consistently exhibit distinct and highly promising advantages in preliminary applications, current scientific research strongly indicates that a comprehensive, in-depth longitudinal assessment spanning a continuous annual cycle is highly recommended. This extended timeframe is indispensable for the systematic and rigorous assessment of their long-term operational performance, durability, and overall reliability. This

comprehensive evaluation encompasses their response to a broad spectrum of seasonal temperature fluctuations and diverse environmental humidity conditions throughout the annual cycle.

Declaration of Conflict of Interest

The authors declared no conflict of interest with any other party on the publication of the current work.

ORCID

Md Azree Othuman Mydin  <https://orcid.org/0000-0001-8639-1089>

References

- [1] T. Reisz, Showpiece city: How architecture made Dubai, Stanford University Press, Palo Alto, CA, 2020. <https://doi.org/10.1515/9781503613867>.
- [2] C. Qiu, H. Yang, and K. Dong, Energy and Thermal Comfort Performance of Vacuum Glazing-Based Building Envelope Retrofit in Subtropical Climate: A Case Study. *Buildings* 15 (2025) 2038. <https://doi.org/10.3390/buildings15122038>.
- [3] J.K. Calautit, H. Sun, J. Li, A. Dik, and M. Mohammadi, Keeping It Simple: Field Testing and Techno-Economic Assessment of a Low-Cost Secondary Quad Glazing for Enhanced Energy Efficiency in Buildings. *Energy and Built Environment* 7 (2026) 766–783. <https://doi.org/10.1016/j.enbenv.2025.03.004>.
- [4] K. Al-Kodmany, The Sustainability of Tall Building Developments: A Conceptual Framework. *Buildings* 8 (2018) 7. <https://doi.org/10.3390/buildings8010007>.
- [5] K. Kiatreungwattana, and L. Simpson, Demonstration and evaluation of lightweight high performance quad-pane windows, Office of Scientific and Technical Information (OSTI), 2021. <https://doi.org/10.2172/1827311>.
- [6] R. Bakker, Smart buildings: Technology and the design of the built environment, Taylor & Francis, London, England, 2020.
- [7] M.B. Bonham, Bioclimatic Double-Skin Façades, Routledge, 2019. <https://doi.org/10.4324/9781315661384>.
- [8] P. Sadooghi, and N.P. Kherani, Thermal Analysis of Triple and Quadruple Windows Using Partitioning Radiant Energy Veils™ with Different Physical and Optical Properties. *Solar Energy (Phoenix, Ariz.)* 174 (2018) 1163–1168. <https://doi.org/10.1016/j.solener.2018.07.034>.
- [9] A. Kralj, J. Kurnitski, M. Žnidaršič, S. Medved, S. Domjan, and M. Halilović, Eliminating Seasonal Energy Storage Needs through Envelope Design: Real-World Cost Analysis of Quadruple Glazing in Office Buildings. *Sustainable Energy Technologies and Assessments* 84 (2025) 104687. <https://doi.org/10.1016/j.seta.2025.104687>.
- [10] A. Mahmoud, Investigating the Impact of Different Glazing Types on the Energy Performance in Hot Arid Climate. *Journal of Advanced Engineering Trends* 42 (2022) 69–84. <https://doi.org/10.21608/jaet.2021.96026.1121>.
- [11] B. Durakovic, and M. Torlak, Experimental and Numerical Study of a PCM Window Model as a Thermal Energy Storage Unit. *International Journal of Low-Carbon Technologies* (2016). <https://doi.org/10.1093/ijlct/ctw024>.
- [12] N. Salih, The Thermal Efficacy of Double, Triple, and Quadruple Glazing under the Extreme Heat Conditions Prevalent in Dubai's Climate (A Field-Based Investigation). *Emirati Journal of Civil Engineering and Applications* 3 (2025) 63–86. <https://doi.org/10.54878/wvr24c41>.
- [13] N. Salih, Glass Facades, Variable and Dubai's Climate. *Emirati Journal of Civil Engineering and Applications* 3 (2025) 87–101. <https://doi.org/10.54878/pn00gj08>.

- [14] N. Salih, A Field Study Compares the Use of Glass with Traditional Materials in the Context of Dubai. A Field Study Compares the Use of Glass with Traditional Materials in the Context of Dubai. *Emirati Journal of Civil Engineering and Applications* 3 (2025) 102–116. <https://doi.org/10.54878/ns25w167>.
- [15] B. Duraković, PCM-based building envelope systems: Innovative energy solutions for passive design, 2020th ed., Springer Nature, Cham, Switzerland, 2020. <https://doi.org/10.1007/978-3-030-38335-0>.
- [16] C. Schittich, G. Staib, D. Balkow, M. Schuler, and W. Sobek, *Glass Construction Manual*, 2nd ed., Birkhauser Verlag AG, Basel, Switzerland, 2007.
- [17] A. Awasthi, K. Vishwakarma, and K.C. Pattnayak, Retrospection of Heatwave and Heat Index. *Theoretical and Applied Climatology* 147 (2022) 589–604. <https://doi.org/10.1007/s00704-021-03854-z>.
- [18] X. Wu, Y. Wang, S. Deng, and P. Su, Climate-Responsive Design of Photovoltaic Façades in Hot Climates: Materials, Technologies, and Implementation Strategies. *Buildings* 15 (2025) 1648. <https://doi.org/10.3390/buildings15101648>.
- [19] M. Hu, K. Zhang, Q. Nguyen, and T. Tasdizen, The Effects of Passive Design on Indoor Thermal Comfort and Energy Savings for Residential Buildings in Hot Climates: A Systematic Review. *Urban Climate* 49 (2023) 101466. <https://doi.org/10.1016/j.uclim.2023.101466>.
- [20] J.D. Musgraves, J. Hu, and L. Calvez, eds., *Springer handbook of glass*, 2019th ed., Springer International Publishing, Cham, Switzerland, 2019. <https://doi.org/10.1007/978-3-319-93728-1>.
- [21] D. Mann, C. Yeung, R. Habets, Z. Vroon, and P. Buskens, Building Energy Simulations for Different Building Types Equipped with a High Performance Thermochromic Smart Window. *IOP Conference Series. Earth and Environmental Science* 855 (2021) 012001. <https://doi.org/10.1088/1755-1315/855/1/012001>.
- [22] H. Koshlak, B. Basok, and B. Davydenko, Heat Transfer through Double-Chamber Glass Unit with Low-Emission Coating. *Energies* 17 (2024) 1100. <https://doi.org/10.3390/en17051100>.
- [23] G. Li, Indoor Environmental Quality in Architecture: A Review. *Building Engineering* 3 (2025) 2375. <https://doi.org/10.59400/be2375>.
- [24] A. Aksamija, *Sustainable facades: Design methods for high-performance building envelopes*, John Wiley & Sons, Nashville, TN, 2013.
- [25] F. Favoino, R.C.G.M. Loonen, M. Michael, G. De Michele, and S. Avesani, Advanced fenestration—technologies, performance and building integration, in: *Rethinking Building Skins*, Elsevier, 2022: pp. 117–154. <https://doi.org/10.1016/b978-0-12-822477-9.00038-3>.
- [26] J. Lstiburek, BSI-001: The Perfect Wall. (n.d.). <https://www.buildingscience.com/documents/insights/bsi-001-the-perfect-wall> (accessed September 22, 2026).
- [27] M. Donn, Simulation and the Building Performance Gap. *Buildings & Cities* 6 (2025) 713–728. <https://doi.org/10.5334/bc.688>.