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Window Glazing for Efficient Daylighting and Energy Saving in Tropical Climate

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A B S T R A C T

Implementing sustainable architectural design solutions, such as daylighting, can effectively decrease the energy consumption of lighting systems. The reduction in energy usage directly affects the energy requirements of heating, ventilation, and air conditioning (HVAC) systems, particularly in buildings located in tropical climates that require more cooling. The paper aimed to minimise energy consumption by achieving a harmonious equilibrium between advantageous natural lighting and excessive solar heat. The study would ultimately lead to reduced energy consumption and provide a guideline for architects to enhance sustainable building designs in Nigeria. This study employed simulation methods to determine the optimal glazing type that achieved satisfactory daylight while effectively controlling thermal heat gain, decreasing cooling load, and minimising energy usage. The study utilises performance simulations to identify glazing types for lowering energy consumption and improving building daylighting performance through rigorous comparative analysis. The simulation procedure was executed using Design Builder software, with Energy Plus as the simulation engine, for a building in Makurdi, Nigeria, considering the Southern-East and Southern-West window orientation. This analysis concludes that choosing the appropriate type of glazing is crucial for minimising energy consumption.

Keywords: Daylighting, energy consumption, Window glazing, simulation, tropical climate

1. Introduction

In pursuing sustainable and energy-efficient building design, architects and engineers increasingly focus on optimising windows (Ayoosu et al., 2021; Ayoosu et al., 2022; Gan et al., 2020). This critical component plays a pivotal role in both daylighting and energy conservation. Windows not only serves as a portal to the external environment but also has a profound impact on the overall energy performance of a building (Kaasalainen et al., 2020). According to Lee et al. (2022) and Ayoosu et al. (2020), integrating windows designed for maximum daylight utilisation and energy savings has become imperative as the demand for environmentally conscious design practices grows.

Well-lit environments can enhance occupant satisfaction and potentially reduce absenteeism (Ayoosu, 2022). Energy-efficient daylighted buildings mitigate detrimental environmental effects by minimising reliance on power-generating plants and their harmful by-products, resulting in cost savings. Significant time and financial resources can be conserved by furnishing architects with explicit guidelines for atria design right from the project's inception, so significantly enhancing the likelihood of achieving an optimised solution.

Therefore, a superior end result can be achieved by allocating greater focus to intricate issues. Numerous daylight simulation programmes are accessible to designers and researchers, enabling them to attain a higher standard of work. In the quest for optimal results, this article explores the intricate relationship between window design, daylighting, and energy efficiency, shedding light on innovative strategies and technologies that can be employed to enhance the performance of windows in buildings. The consideration was on glazing solutions to WWR as critical elements of window optimisation, offering insights into how these strategies contribute to creating a healthier, more comfortable, and environmentally responsible built environment.

This study uses the Energy Plus engine in Design builder simulation programme to determine the most suitable glazing type for a bedroom model with an optimal 30% window-to-wall ratio (Ayoosu et al., 2021), achieving a daylight autonomy of over 50%. The study compares the energy consumption statistics of six different glass types with varying U values and transmittance.

1.1 Review of Previous Studies

Ignacio Acosta et al. (2016) quantified daylight autonomy and useful daylight illuminance within a room for various window models in order to analyse the results acquired. The window's form, size, and location vary, as does the reflectance of the room's interior surfaces. As determined in the study, daylight autonomy indicates the extent to which artificial illumination is not required in space, resulting in energy savings in power usage. An optimal range for daylight autonomy is often between 50% and 100%, with a target illuminance of 300 lx to enhance visual comfort (I Acosta et al., 2016; Shafavi et al., 2020).

As reported in Alhagla et al. (2019), Krarti conducted a study to examine the effects of building geometry, window size (WWR), and glazing type on daylighting performance in four different geographical areas in the United States. The study discovered a substantial influence on energy conservation with daylighting implementation. Increasing the windows' size or improving the glazing's transparency enhances daylighting's advantages. The research has demonstrated that a daylighting aperture exceeding 0.3 will reduce energy savings. He concluded that in the case of commercial buildings with glass transmittance values exceeding 0.5, increasing the window area to floor area ratio beyond 0.5 does not result in substantial energy savings from daylighting. The WWR > 0.3 for reduced energy savings was consistent with the study of Ayoosu et al. (2021), which found that 30% WWR was optimal for daylighting in tropical climate. Therefore, the current study adopts the 30% WWR as optimal for the study while varying the grazing.

In a study conducted by Hee, according to Alhagla et al. (2019), it was demonstrated that optimisation approaches provide a harmonious solution for resolving the conflicts involved in choosing an energy-efficient window glazing for a structure. Based on past studies, the study presented the effects of window glazing on the energy and daylighting efficiency of buildings. Conducting a techno-economic evaluation is advisable to select the appropriate glazing for a building. Because of its greater prices, dynamic glass is better suited for installation in structures that require exceptional performance in terms of daylighting and energy conservation, such as commercial buildings.

Daylight autonomy began a series of annual daylight measurements, now widely known as 'dynamic daylight metrics' (Acosta et al., 2019). It refers to the proportion of annual daylight hours during which a specific location in space is exposed to a predetermined degree of illumination. It is a crucial consideration in designing energy-efficient and occupant-friendly buildings, aiming to harness natural light to the maximum extent possible while minimising the reliance on artificial lighting. It represents a holistic approach to sustainable design, encompassing energy efficiency and human-centric considerations (Ayoosu, 2022). The minimal illuminance threshold is determined by authoritative lighting references such as the IESNA Lighting Handbook (Lakhdari et al., 2021).

Cooling load through glazing design is a critical aspect of building design, particularly in the context of energy efficiency and indoor comfort. Glazing, or glass in windows and facades, plays a significant role in determining the amount of solar radiation that enters a building. Managing this solar heat gain is essential to reduce the cooling load on the building's HVAC (Heating, Ventilation, and Air Conditioning) systems. The factors influencing cooling load through glazing design include the solar Heat Gain Coefficient (SHGC), which is a critical parameter that quantifies the amount of solar radiation allowed to pass through the glazing. It represents the fraction of solar radiation entering the building through the windows. Low SHGC values are desirable in warm climates to minimise heat gain, while higher values may be preferred in colder climates to harness solar heat for passive heating (Aguilar-Santana et al., 2020; Larcher et al., 2016).

On the other hand, visible Light Transmission (VLT) measures the percentage of visible light that can pass through the glazing. Balancing VLT with SHGC is crucial to ensure that the glazing provides adequate daylight while minimising unwanted heat gain. Where the U-Factor measures the rate of heat transfer through the glazing. A lower U-factor indicates better insulation properties, essential in heating and cooling seasons. Energy-efficient windows typically have a low U-factor.

Glazing Orientation and Shading: The orientation of glazing on a building and external shading elements significantly impact the cooling load. Properly designed shading devices, such as overhangs, fins, or external blinds, can reduce direct sunlight exposure and help control heat gain. Insulated Glazing Units (IGUs), commonly known as double or triple glazing, consist of multiple glass panes separated by air or gas-filled spaces (Aguilar-Santana et al., 2020; Chen et al., 2023). These units enhance insulation and reduce heat transfer, contributing to energy efficiency. Low-E Coatings: Low-emissivity coatings are applied to glazing surfaces to reduce the emissivity of the glass, limiting the amount of radiant heat transfer. This technology allows windows to reflect some of the infrared radiation while maintaining high visible light transmission. Some advanced glazing technologies, called dynamic glazing, can dynamically adjust their properties based on environmental conditions (Michael et al., 2023). Electrochromic and thermochromic windows, for example, can change tint or transparency to optimise daylighting and thermal performance (Cuce & Cuce, 2016; Larcher et al., 2016).

Daylighting, the strategic use of natural light, is a fundamental aspect of interior design that significantly impacts visual comfort. One critical consideration in daylighting design is the uniform distribution of daylight (daylight uniformity) within a space, particularly in bedrooms where occupants spend considerable time. Therefore, a well-designed space should have a balanced distribution of daylight to ensure that no areas are too bright or too dim, creating a comfortable and visually pleasing environment (Ayoosu, 2022).

1.2 Residential window Glazing in Nigeria

In Nigeria, as shown in Fig. 1, residential buildings often use a variety of window glasses to suit different needs and preferences. The choice of glass depends on factors such as climate, energy efficiency, security, privacy, and aesthetic preferences. Some common categories of window glasses used in Nigerian residential buildings include:

Float Glass: This is a basic category of clear glass widely used for windows. It is manufactured by floating molten glass on top of molten tin, resulting in a smooth and flat surface.

Tinted Glass: Tinted glass is treated with a film or coating to reduce glare and block out a certain amount of sunlight and UV rays. It helps in maintaining privacy and controlling the temperature inside the building.

Reflective Glass: Reflective glass has a metallic coating that reflects a significant portion of sunlight, reducing heat gain inside the building. It is often used in hot climates to improve energy efficiency and provide privacy.

Low-E Glass (Low Emissivity): Low-E glass has a thin coating that reflects heat while allowing light to pass through. It helps regulate indoor temperature, reduce energy consumption for heating and cooling, and protect furniture from UV rays.

Patterned Glass: Patterned glass is textured or embossed with various designs for decorative purposes. It provides privacy while allowing light to pass through, making it suitable for bathrooms and other areas where privacy is desired.

Laminated Glass: Laminated glass consists of two or more layers of glass bonded with a durable interlayer, usually made of polyvinyl butyral (PVB). It is strong, resistant to impact, and holds together when shattered, reducing the risk of injury from broken glass.

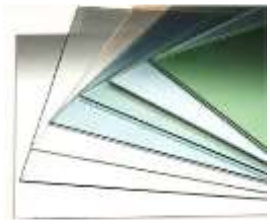
Tempered Glass: Tempered glass is heat-treated to increase its strength and durability. It is several times stronger than ordinary glass and shatters into small, blunt pieces when broken, reducing the risk of injury. It is commonly used in windows that require extra safety and security.

Double-Glazed Glass: Double-glazed glass consists of two panes of glass separated by a space filled with air or inert gas. It provides better insulation against heat, cold, and noise compared to single-pane glass, making it suitable for improving energy efficiency and acoustic performance in residential buildings.


Float Glass


Tinted Glass


Reflective Glass


Low-E Glass


Patterned Glass


Laminated Glass


Tempered Glass


Double Glazed Glass

Fig. 1*:* Window glazing category used on residential buildings in Nigeria

However, the categories of glasses are further classified into types based on critical optical and thermal properties, as shown in the table. These types are the variables the study explores to establish the suitability in the tropical climate of Makurdi.

Table 1: Properties of Glazing Types (Alhagla et al., 2019; Ayoosu, 2022)

Glazing type	**Tau-vis**	**SHGC**	**U-Value Wm^{-2} K**	**Visual transmittance**	**Visual transmissivity**
Glazing single plane 88	0.88	0.82	5.82	88%	96%
Glazing double plane clear 80	0.80	0.72	2.27	80%	87%
Glazing Double plane Reflective	0.65	0.28	1.63	65%	71%
Glazing Tau-vis	0.70			70%	76.3%
Glazing Double plane Low E- Argon	0.65	0.27	1.32	65%	71%
Triple glazing double plane -Low E-	0.47	0.23	0.57	80%	80%

Electrochromic Glazing	0.98	60%	65.404%

2. Method and Materials

The research technique comprises one primary element. It focuses on analysing various types of glazing to determine the suitable performance criteria for glazing systems in buildings in the hot-humid climate of Nigeria. In addition, a computer simulation tool is utilised to design and select glazing systems. The engine simulates the energy used for cooling, lighting, and daylight through windows. The study involved two bedrooms in a model in a three-bedroom house in Makurdi, Nigeria. The orientation of the bedroom windows is south-east and south-west, and they were chosen because of the critical sun path effect. The model is shown in Figure 2.

According to a recent study by Ayoosu (2022), daylight autonomy describes the area above 300 lux for 50% of the occupied hours. The acceptable daylight uniformity for visual comfort can vary depending on factors such as the specific application, the type of space, and individual preferences. However, a uniformity ratio of around 0.5 to 0.8 is generally considered acceptable for visual comfort in indoor environments. This means that the illuminance levels across a space should not vary too greatly, ensuring that no overly bright or dark areas can cause discomfort or visual strain for occupants. Therefore, these benchmarks were used for the evaluation of daylighting.

a) Floor plan

b) North view

c) East view

d) South window view

Fig. 2: Case study building

3. Result and Discussion

3.1 Daylighting

Table 2: Simulation Result for daylight performance of different glazing types

Glazing Type	Space	Uniformity ratio (Min / Avg)	sDA
Glazing single clear no shading (Base case)	Master Bed Room	0.11	76.25
	Bed Room1	0.11	93.48

Glazing double plane clear	Master Bed Room	0.11	72.5
	Bed Room1	0.11	93.48
Glazing Double plane Reflective	Master Bed Room	0.12	38.9
	Bed Room1	0.1	39.2
Glazing Tau-vis	Master Bed Room	0.12	48.75
	Bed Room1	0.11	47.83
Glazing Double plane Low E- Argon	Master Bed Room	0.11	71.88
	Bed Room1	0.12	93.48
Triple glazing double plane -Low E	Master Bed Room	0.11	72.5
	Bed Room1	0.12	93.48
Electrochromic Glazing	Master Bed Room	0.11	70.63
	Bed Room1	0.13	92.39

Table 2 presents the simulation results comparing the daylight performance of various glazing types in two specific spaces: Master Bedroom and Bedroom 1. The performance is measured by two metrics: Uniformity Ratio (Min/Avg): This ratio indicates how evenly daylight is distributed across the space. A lower value signifies greater variation, with some areas receiving significantly less light than the average. Meanwhile, sDA (Spatial daylight autonomy) represents the overall amount of daylight available in the space throughout the year. It's measured in percentages, with higher values indicating better daylight penetration. The Simulated image Result for daylight performance of different glazing types is presented in Table 3 for visualisation.

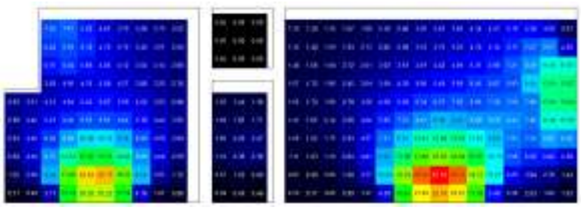
Base Case Performance: The baseline scenario uses single clear glazing with no shading. It achieves a uniformity ratio of 0.11 in both bedrooms, suggesting a slightly uneven distribution. The sDA values are high, with 76.25% in the Master Bedroom and 93.48% in Bedroom 1, indicating good daylight availability. It, therefore, suggested that daylight quality in the base case needs enhancement.

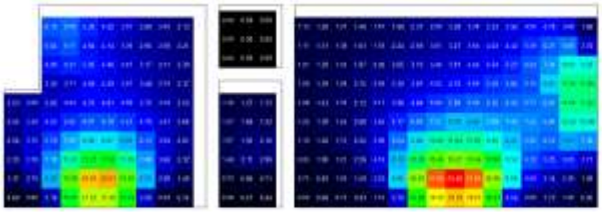
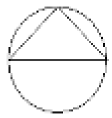
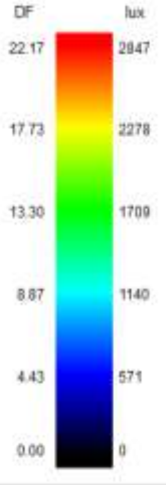
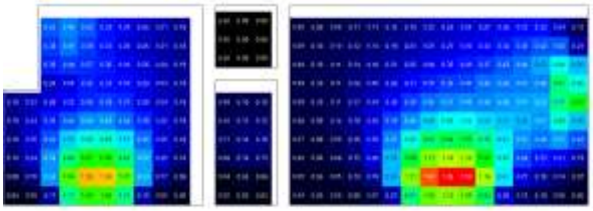
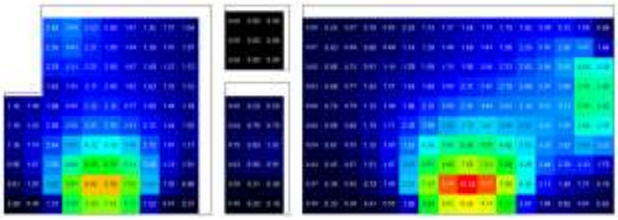
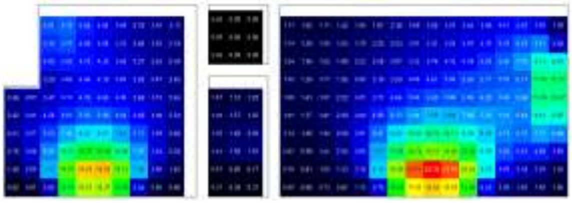
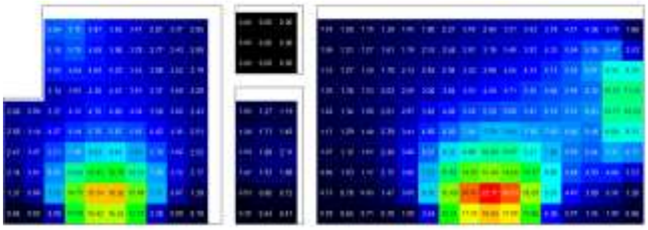
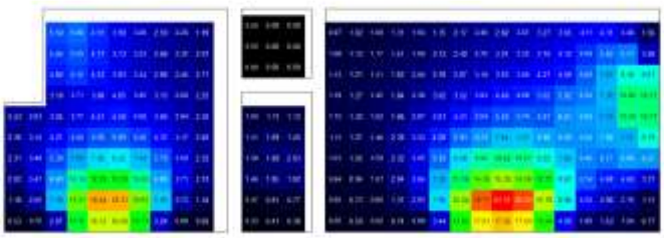
3.2 Impact of Glazing Type

Double Glazing: Double-plane clear glazing performs similarly to the baseline in terms of uniformity but has slightly lower sDA, especially in the Master Bedroom. Reflective Glazing: Double-plane reflective glazing significantly reduces sDA in both bedrooms (around 50% drop) while maintaining a similar uniformity ratio. This suggests it reflects a substantial amount of daylight outwards. Tau-vis glazing offers a moderate reduction in sDA (around 30% drop) compared to the base model, with a slight improvement in uniformity in the Master Bedroom. Low-E Glazing: Double-plane Low-E Argon and triple Low-E glazing show minimal impact on uniformity and a slight decrease in sDA compared to the base model in the Master Bedroom. Bedroom 1 maintains its high sDA with these glazing types. Electrochromic glazing, on the other hand, has a minor effect on uniformity and results in a small decrease in sDA compared to the baseline in the Master Bedroom. Bedroom 1 shows a slightly lower uniformity but maintains good daylight availability.

The uniformity ratio remains relatively consistent across most glazing types, suggesting minor variations in light distribution within the bedrooms. The impact on sDA varies depending on the glazing property. Reflective glazing significantly reduces daylight penetration, while Low-E and electrochromic glazing have a milder effect with consistency.

Table 3: Simulated image Result for daylight performance of different glazing types

Glazing type	Simulation result of illuminance		Scale
	Bedroom 1	Master Bedroom	
Glazing single clear no shading (Base case)			

Glazing double plane clear		 
Glazing Double plane Reflective		
Glazing Tau-vis		
Glazing Double plane Low E- Argon		
Triple glazing double plane -Low E		
Electrochromic Glazing		

3.3 Energy savings

Fig. 3 summarises the simulated impact of different glazing types on the energy needs for heating and cooling in two rooms (Master Bedroom and Bedroom 1). The focus is on reducing the cooling energy required for these spaces. Glazing types include single clear (Base Case), double clear, double reflective, Tau-vis, double low-emissivity (Low-E) with Argon gas filling, triple low-E, and electrochromic glazing. The spaces were used for the simulations to be conducted in the two-room categories.

Average Annual Heat Gain [kW]: This shows the estimated annual heat gain through each glazing type for the respective rooms. Lower values indicate less heat entering the space, potentially reducing cooling needs in summer. Average Annual Sys Sensible Cooling Energy [kWh displays the simulated annual energy consumption for the cooling system associated with each glazing type in each room. Lower values indicate less energy needed for cooling.

Double pane with Low-E and Argon appears to be the most energy-efficient option: This glazing type (Double plane Low-E- Argon) has the lowest average annual cooling energy consumption for both rooms, indicating it allows less unwanted heat gain compared to other options. The triple glazing with double Low-E is slightly less efficient than double Low-E with Argon: While offering good performance, triple glazing with double Low-E shows marginally higher cooling energy consumption than double Low-E with Argon. Reflective and Tau-vis glazing provide moderate efficiency: These glazing types (Double plane Reflective and Tau-vis) demonstrate a moderate reduction in cooling energy needs compared to the Base Model.

Single clear glazing (Base Model) and electrochromic glazing have the highest cooling energy consumption: Both single clear and electrochromic glazing show the highest values in cooling energy consumption, suggesting they allow the most heat gain and require the most energy for cooling. It's worth noting that electrochromic glazing offers better control over daylight.

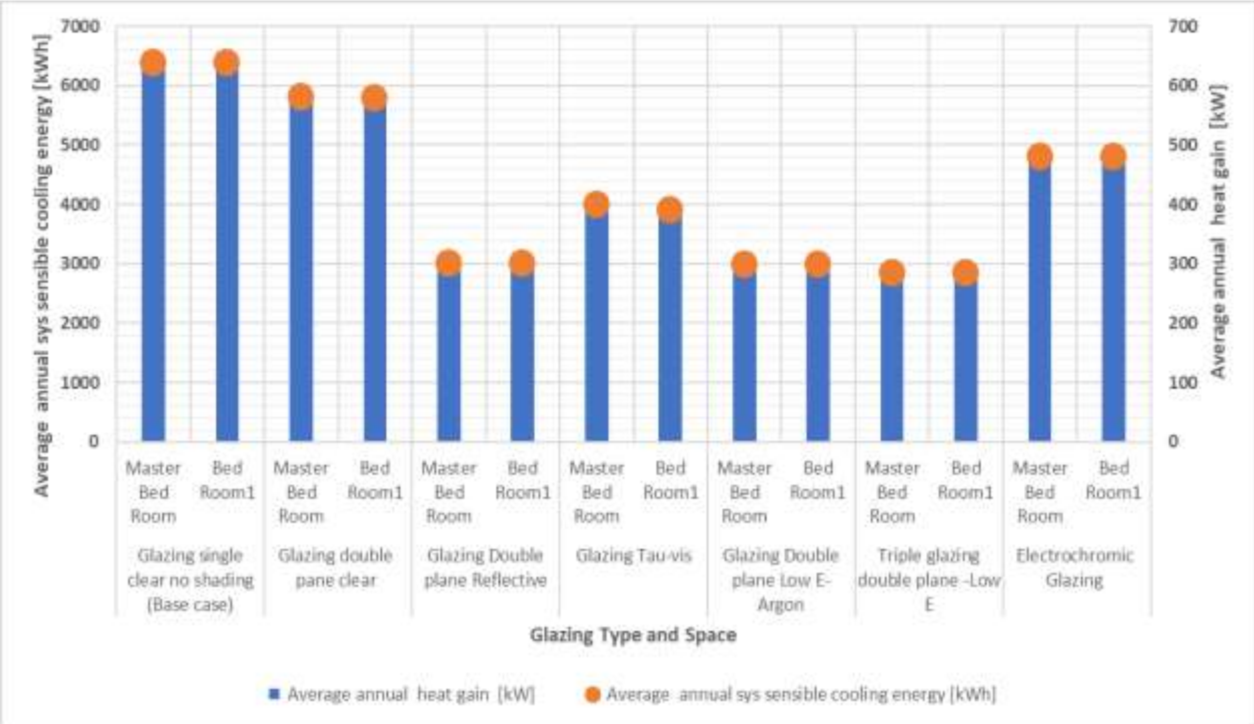


Fig. 3: Simulation Result for energy needs for heating and cooling in two rooms of different glazing types

4. Conclusion

Based on the simulation results, for both Master Bedroom and Bedroom 1, the Double Glazing with Low-E Argon offers the best balance between energy efficiency and daylight availability.

Energy Savings: Double Glazing with Low-E Argon boasts the second-lowest average annual heat gain and the lowest annual cooling energy requirement compared to other glazing types. This translates to significant energy cost savings for heating and cooling the bedrooms.

Daylight Availability: While Double Glazing with Low-E Argon has a slightly higher uniformity ratio (indicating a more even distribution of daylight) compared to some options, it still provides sufficient daylight (above 70% for both rooms). The Triple Glazing with Double Low-E offers marginally better energy performance, but the difference is minimal compared to Double Glazing with Low-E Argon. Electrochromic glazing offers similar energy savings to Double Glazing with Low-E Argon but comes at a potentially higher cost and may require additional control systems.

Therefore, considering energy efficiency and daylight availability, Double Glazing with Low-E Argon presents the most compelling choice for these bedrooms. Additional Considerations like Project budget: Double Pane Clear might be a viable alternative if budget is a major concern, but expect higher cooling costs. Double Glazing Reflective could be considered for further heat gain reduction in very hot climates, but be aware of the potential impact on daylight. The visual appearance of the glazing (transparency, reflectivity) might influence the final decision.

However, for a more comprehensive analysis, factors occupant preferences and wind placement should also be considered.

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