

Evaluating Visual Comfort in Semi-Transparent Perovskite Solar Window Integration for Building Design in Qatar's Hot Climate

Haneen Nsair^{1,*}, Abdulla Alnuaimi¹, Raffaello Furlan¹, Abdalrahman Alhndawi², Heba Alqub³

¹Department of Architecture and Urban Planning, College of Engineering, Qatar University, Qatar

²Faculty of Civil Engineering, Department of Environmental Engineering, Universiti Teknologi Malaysia (UTM), Malaysia

³Faculty of Engineering and Technology, Department of Architecture, Applied Science Private University, Jordan

Received October 16, 2024; Revised February 18, 2025; Accepted March 5, 2025

Cite This Paper in the Following Citation Styles

(a): [1] Haneen Nsair, Abdulla Alnuaimi, Raffaello Furlan, Abdalrahman Alhndawi, Heba Alqub, "Evaluating Visual Comfort in Semi-Transparent Perovskite Solar Window Integration for Building Design in Qatar's Hot Climate," *Civil Engineering and Architecture*, Vol. 13, No. 3, pp. 1480 - 1495, 2025. DOI: 10.13189/cea.2025.130304.

(b): Haneen Nsair, Abdulla Alnuaimi, Raffaello Furlan, Abdalrahman Alhndawi, Heba Alqub (2025). *Evaluating Visual Comfort in Semi-Transparent Perovskite Solar Window Integration for Building Design in Qatar's Hot Climate*. *Civil Engineering and Architecture*, 13(3), 1480 - 1495. DOI: 10.13189/cea.2025.130304.

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Abstract Among various solutions in sustainable building design, optimum interior daylight is vital in improving visual comfort and occupants' well-being. Semi-transparent perovskite solar windows have emerged as a promising solution because they offer energy generation and enhance daylighting performance. In hot desert climates, such as Qatar, the high intensity of solar radiation poses various challenges to achieving a comfortable visual environment. This paper focuses on the ST-PSW's impact on daylighting and glare issues. The research will determine an optimum value of WWR and VLT for office buildings in Qatar that provides a better balance between natural light intake and visual comfort. Simulations were performed in Grasshopper for Rhino, while daylighting analyses were performed using Radiance software. The outcome of these analyses indicates that 40% WWR with a VLT of 0.4 is an ideal solution providing the most daylight yet limiting glare. However, supplementation through artificial light sources may be required in certain areas. A 60% WWR with the same VLT allows for better distribution of natural light; however, this may involve the use of shade in winter months. The best combination is 60% WWR with a VLT value of 0.3, which presents the optimal distribution between daylight and glare control, limiting the need for any extra light source or shading. The research findings will contribute to developing intelligent building strategies and play to Qatar's 2030 vision for

sustainable development.

Keywords Visual Comfort, Semi-Transparent Perovskite, Solar Window, Sustainable Building Design, Hot Desert Climate, Qatar

1. Introduction

In the rapidly evolving landscape of sustainable architecture, integrating semi-transparent perovskite solar windows (ST-PSWs) offers a revolutionary opportunity to redefine how buildings in extreme climates, such as Qatar, balance visual comfort with energy efficiency. Incorporating these windows into architectural design presents a transformative approach to enhancing visual comfort, particularly in Qatar's challenging climatic conditions, while simultaneously addressing the imperative of energy efficiency. In Qatar's hot climate, cooling systems dominate electricity consumption, creating a dual challenge of high energy use and occupant comfort. Saffouri et al. [1] report that air conditioning constitutes about 36% of annual electricity consumption, demonstrating the need for innovative solutions that can reduce cooling loads while maintaining thermal comfort.

Visual comfort is a fundamental architectural design element, critically influencing occupant well-being, productivity, and overall satisfaction within indoor environments. Achieving the optimal balance between aesthetic appeal and functional performance is particularly challenging when integrating innovative materials such as perovskite solar cells. These materials must ensure a high quality of natural light within interior spaces while contributing to renewable energy production. The successful deployment of perovskite solar windows requires careful consideration of light transmittance and opacity. This maximizes daylight availability without compromising visual comfort, creating energy-efficient and comfortable living and working spaces.

Perovskite solar cells (PSCs) are efficient and transparent; thus, they can be incorporated into smart window technologies. Li et al. [2] identify that such self-powered smart windows can look like tinted glass and do not interfere with the building's external view. This further creates a means of energy production but, at the same place, minimizes on-building electrical wiring that may destroy building architecture. Yet, the challenge remains in the trade-off; the optimization of the balancing of light transmittance and performance of the device is such that too much opacity will reduce daylight availability and eventually mask visual comfort.

High temperatures and severe sunlight influence the right approach to a window design for Qatar's climate. Khan [3] further discussed that to lighten the energy load from residential buildings in Qatar, integrating renewable solutions, like rooftop solar photovoltaic, is extremely important. In this respect, the placement and sizing of windows become crucial since they gain both thermal performance and daylighting, which is essentially required for occupants' comfort. This hypothesis is further supported by the findings of Hammad et al. [4], which demonstrated that window design may affect energy performance and lighting in buildings.

Apart from that, it is worth mentioning the shading devices. The experimental research by Lapisa [5] proves that providing shades for windows can substantially improve tropical thermal-visual comfort, meaning its methods might become workable even for Qatar. Roscam and Osterodt [6] presented dynamic glazing technologies, an alternative to achieving much more visual comfort by regulating daylight intake and energy performance. These glazing technologies can adjust according to the changing light conditions to improve the comfort of the occupants and reduce energy use.

Apart from the physical characteristics of the window, the methodology for evaluating visual comfort is changing. The new machine learning method proposed by Tzouvaras et al. [7] for real-time visual comfort assessment can help validate using semi-transparent solar windows in occupied space. This non-intrusive approach will permit continuous monitoring and possible modification of indoor conditions

to meet visual comfort requirements without a loss of energy efficiency.

These semi-transparent solar windows will also be designed by considering passive solar design principles and highlighting natural light and thermal comfort. Gholami and Ross [8] consider a genetic programming application connected with passive solar building design, claiming that such a design must be holistic, considering thermal and visual comfort. This is very important in Qatar due to its harsh climate, which demands new design solutions that allow maximum natural light while minimizing heat gain.

Besides that, optimization in window location and window design plays a vital role in high daylight performance. According to Rais et al. [9], evaluation parameters of visual comfort, such as daylight factor and glare control, are indispensable during the design process. These parameters have been allocated an evaluation framework through BREEAM to ensure that buildings meet the stipulated standards necessary for comfort among occupants.

The impact of semi-transparent perovskite solar windows can thus be extended to scales that exceed the single building and speak to a more general urban planning consideration. Mühlbauer [10] gives an overview of the potential for BIPV in Qatar, underlining their potential contribution to renewable energy sources while providing new impulse to the aesthetic quality of the urban environment. Such a double role is particularly relevant in a region like this, where energy efficiency and visual comfort are increasingly at the forefront of concerns.

Integrating semi-transparent perovskite solar windows into building design in Qatar may be one of the most promising avenues to improve occupants' visual comfort while responding to energy efficiency. Each of the mentioned layers-window design, occupant comfort, and energy performance interacts in a complementary way with the other inner layers and requires a comprehensive approach: new materials, enhanced assessment methodologies, and strategic design principles. As this field keeps evolving, ongoing research and development will be needed to optimize such technologies for Qatar's specific climatic and cultural context.

The main objective of this study is to assess the incorporation of semi-transparent perovskite solar windows (ST-PSW) into architectural designs in Qatar, particularly emphasizing the enhancement of visual comfort for inhabitants. This research aims to reconcile the advantages of natural daylight with energy efficiency in Qatar's distinctive climate while addressing challenges, including glare and heat gain. The study has three main goals. The first is to find the best window-to-wall ratio (WWR) and visible light transmittance (VLT) that improve daylight performance while maintaining visual comfort. The second is to see how well ST-PSW reduces the need for artificial lighting, which saves energy. Lastly, the third objective is to determine whether these solar windows can

serve as a sustainable solution that aligns with Qatar's 2030 Vision for energy-efficient building strategies. This study employs extensive simulations and daylighting assessments to deliver practical insights into how advanced solar technologies might improve visual comfort and energy efficiency in contemporary architectural projects in arid desert regions such as Qatar.

2. Literature Review

2.1. Semi-Transparent Perovskite Solar Windows (ST-PSWs)

Solar windows, also known as BIPV windows, are an innovative and rapidly developing technology for sustainable applications [11]. These windows transform glass surfaces into electricity-generating assets, providing a more aesthetically pleasing and efficient alternative to traditional solar panels [12]. Additionally, solar windows enable daylight harvesting, allowing natural light to enter during the daytime [13]. Fig. 1 shows different types of solar windows installed within the building design.

Multiple generations of photovoltaic cells are being explored for integration into solar windows. While technologically mature, first-generation silicon-based cells face limitations due to their opaque nature and efficiency constraints [16]. Crystalline silicon (c-Si) PV cells have good efficiency but lack aesthetic appeal for building windows due to limited color options [17]. Second and third generations of PV systems, including amorphous silicon (a-Si), cadmium telluride (CdTe), organic, and Perovskite cells, exhibit promise for solar window

applications due to their tunable transparency and more straightforward fabrication [18-20].

Perovskite solar cells (PSCs) have seen remarkable advancements, achieving efficiencies comparable to inorganic photovoltaics and surpassing traditional materials like CdTe within a decade [21]. Their cost-effective production positions them as a compelling, low-cost alternative to commercial photovoltaic options [22]. Semi-transparent PSCs (ST-PSCs) are particularly promising for power-generating windows because of their outstanding photoelectric properties and adaptable design [23]. Research has demonstrated that ST-PSCs can achieve efficient performance with adjustable transparency by varying the perovskite layer thickness [24]. Additionally, ST-PSWs have been shown to enhance Useful Daylight Illuminance (UDI) and reduce discomfort glare (DGP) by 12-23% compared to clear glass [25]. They also offer superior visual comfort with higher transparency (42.4%) compared to amorphous silicon cells (15%) [26, 27]. A study reviewed the potential and transparency advantages of PSCs for solar windows, showing their ability to achieve 6.4 efficiency at full transparency or 14.6 efficiency at 0.9 transparency, and that they outperform silicon solar cells under low and diffused light conditions [28]. Consequently, they are chosen for their significant benefits in integrated building applications, as they offer an ideal balance of energy generation, visual comfort and daylight optimization. Their high transparency, efficient performance and cost effectiveness make them a promising solution for building-integrated applications, especially in hot climates like Qatar. Fig. 2 shows contrasting levels of transparency for semi-transparent Perovskite solar cell (ST-PSC).

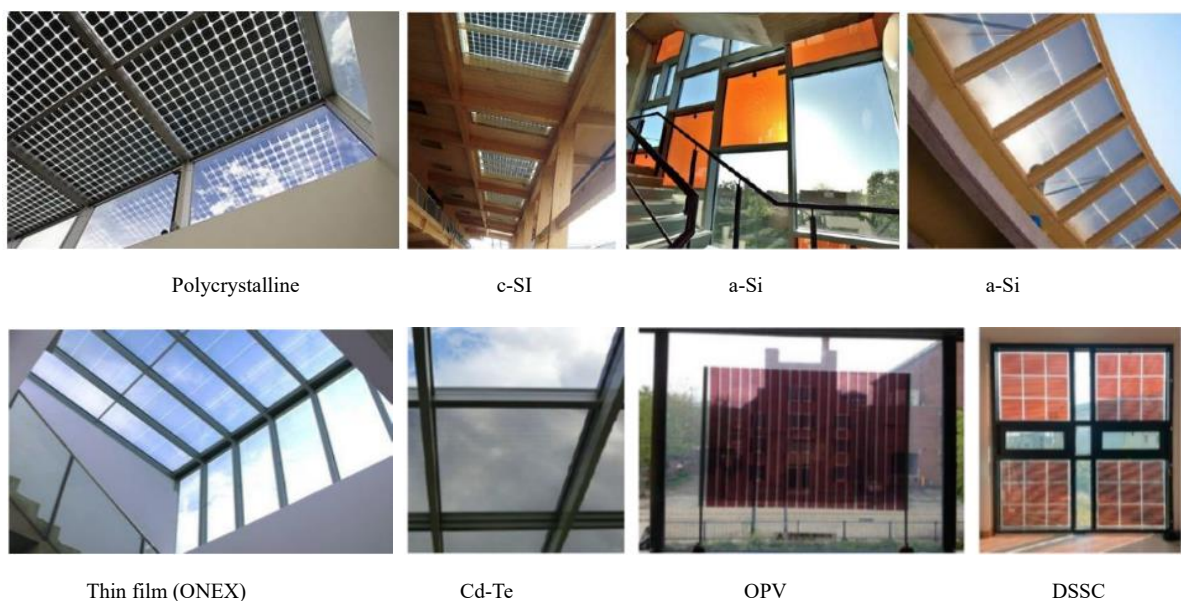


Figure 1. Integrated window with various PV cell material types [14-15]

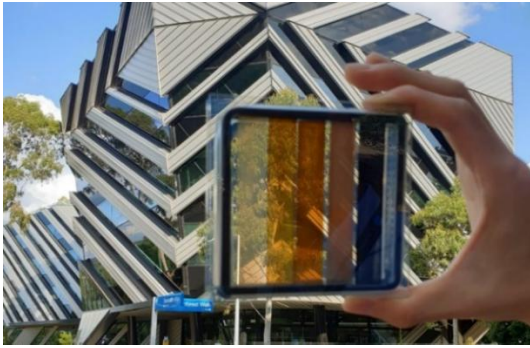


Figure 2. ST-PSW with different levels of light transparency [29]

2.2. Visual Comfort Considerations of Building Design

Efficient daylighting is crucial for enhancing occupant well-being in modern buildings. Prioritizing visual comfort in indoor design can maximize the benefits of natural light, with building fenestrations playing a pivotal role. A study examines how visual comfort, especially daylight, is assessed in LEED, which awards 1-3 points for daylight performance in office buildings [30].

The rise of commercial solar windows highlights the growing emphasis on indoor visual comfort in building engineering. Results indicate that proper percentage of STPV transparency improves visual comfort [31]. Additionally, it was discovered that, in comparison to traditional double glazing, CdTe PV windows may significantly increase lighting distribution uniformity and lower glare concerns [32]. Another study investigated the optimal performance of light shelf photovoltaics for improving daylight distribution and energy savings in Saudi Arabia's hot climate. It found that it provided uniform daylight, except in winter [33]. Hence, researchers increasingly focus on visual comfort issues related to ST-PV windows in buildings.

Metrics like DGP and UDI are essential for evaluating indoor visual comfort. UDI measures the amount of daylight illumination based on hourly weather data and is a crucial variable for assessing daylighting effects on visual discomfort. DGP, which considers vertical eye illuminance, is essential for understanding occupants' lighting perception [34]. These metrics determine how well STSW can enhance visual comfort while maintaining energy efficiency.

In Algeria's semi-arid climate, STPV windows have demonstrated potential for improving UDI values and reducing high DGP values, thus enhancing visual comfort [35]. However, most BIPV studies focus more on energy and thermal performance, often overlooking visual comfort considerations [16]. Research has shown that integrating STSW not only generates annual electric energy output comparable to commercial a-Si cells but also serves as solar control films, blocking unwanted solar gains and improving indoor visual comfort [25].

Other research evaluated daylight performance in side-

lit offices with windows partially covered by CdTe PV glazing. According to their models, more PV glazing coverage enhanced working hours with reduced glare ($DGP \leq 0.35$) and desirable illumination levels ($100 \text{ lux} \leq UDI \leq 2000 \text{ lux}$) [14]. Similarly, the research found that perovskite-based PV windows significantly reduced high DGP occurrences from 49% with clear glass windows to 16% in London [25]. Furthermore, a study used RADIANCE to evaluate CdTe PV windows with different visible transmissions and WWRs, emphasizing the effects of these variables on visual comfort [32].

These insights into the performance of STPV windows underscore their potential to enhance visual comfort while maintaining energy efficiency. In this context, the chosen ST-PSWs offer significant advantages, its high transparency ensures adequate daylight entry, contributing to enhanced UDI values while reducing glare discomfort and unwanted heat gains, all while generating renewable energy. However, there is a notable research gap in evaluating the performance of such system in Qatar's climate. Therefore, this study aims to explore the integration of ST-PSWs further and optimize their performance to address visual comfort issues and improve overall building sustainability in Qatar's region.

2.3. Building Design in Qatar Climate

2.3.1. Building Design Considerations

In building design, while STPV systems have the potential to reduce indoor illuminance levels, offering advantages in glare reduction, design considerations such as room depth, WWR, VLT, and orientation remain crucial. Most of the studies, which highlighted various BIPV scenarios, pointed to the impact of the WWR on daylight performance and visual comfort [36]. Furthermore, daylighting studies have revealed that different levels of VLT impact UDI levels [37], [38]. In this study, a STPV system was used to introduce daylighting into an interior room of a building to measure vertical daylighting, which was claimed that this lessens the demand for artificial illumination during the day [39].

For office buildings in Qatar, the average WWR typically ranges from 30% to 50%. This range aligns with recommendations for other hot climates, aiming to balance natural light benefits and energy efficiency by minimizing cooling loads while maximizing daylight use [40]. Hence, for this study, a WWR of 40% will be used to investigate the effect of VLT on visual comfort. To assess the impact of increasing WWR on visual comfort, a second case with a WWR of 60% will also be examined. Also, this study chooses VLT values from (0.2 to 0.7) for ST-PSW to evaluate visual comfort, as this range balances natural light benefits with energy efficiency, minimizing cooling loads while maximizing daylight use; high VLT values enhance daylighting and reducing artificial lighting reliance, while

lower values decrease cooling demands [41].

In addition to these parameters, the study employs room dimensions (4.00 × 5.00 meters, with a height of 3.2 meters) based on typical office configurations in Qatar. These dimensions provide a practical and realistic framework for evaluating daylighting performance and visual comfort. Smaller rooms might amplify glare, while larger rooms could dilute the benefits of natural light. Therefore, by using standard dimensions, the study ensures that its findings are applicable to common office environments and meet international standards for daylighting simulations [42].

2.3.2. Qatar Climate

The study was performed in Qatar, which has a hot desert climate (Köppen climate classification Bwh). According to climate data, summer temperatures often exceed 38 °C and can reach over 45 °C. In Doha, June has the highest number of sunshine hours. Average monthly temperatures range from 18 °C in January to 36 °C in July and August, with daily sunlight averaging 8 hours in winter and 13 hours in summer.

Previous research in Algeria's semi-arid climate has shown that BIPV windows can significantly improve visual comfort in office buildings, where the optimum design for BIPV windows included PV modules with double glazing medium WWRs and variable VLT depending on orientation [43]. A similar study in Saudi Arabia analyzed the visual comfort of ST-BIPV windows based on perovskites; it indicated that transmissions between 50–70% were optimal for comfortable daylight in the south façade [44].

In Qatar's hot climate, cooling systems dominate electricity consumption, creating a dual challenge of high energy use and occupant comfort [45-47]. ST-PSWs have the potential to reduce cooling loads. However, high ambient temperatures and intense solar radiation reduce the power conversion efficiency (PCE) of perovskite materials, accelerating their thermal degradation. Also, dust accumulation is a noteworthy concern within this region significantly reduces solar gain, necessitating frequent cleaning to maintain cell efficiency [48].

Despite the challenges posed by high temperature, dust accumulation, and thermal losses, the ability of ST-PSWs to modulate light transmission and reduce heat gains positions them as a promising solution for balancing visual and thermal comfort besides contributing to energy efficiency while producing renewable energy, particularly when paired with advanced strategies, such as integrating coating technologies and electrostatic cleaning systems [49].

The design of ST-PSWs can be optimized by suitable transparency levels for maximizing energy-saving potentials in extreme climates. Therefore, selecting this promising technology with appropriate transparency and size design parameters is crucial to determine the visual comfort efficiency used within Qatar climate to optimize the benefits of BIPV systems in such an environment.

2.3.3. PVS Technology in Qatar

Qatar, driven by rapid urbanization, is a leading Middle Eastern country embracing modern architectural designs [50] and aligns with the Qatar National Vision 2030's focus on sustainable development in sectors such as construction and housing. In response to rising electricity consumption in residential buildings due to urbanization and population growth, the government has initiated efforts to integrate solar power through large photovoltaic systems and promote small and medium-sized BIPV systems in private homes. These systems provide renewable energy solutions tailored to the local climate and architecture while addressing economic and social advantages [10].

Perovskite research in Qatar has made significant advancements, particularly in photovoltaics. Researchers at Hamad Bin Khalifa University have developed a PSC that has shown improved electron mobility and achieved a high efficiency of 17.1% and a high optical transmittance in the visible range that promotes stable, long-lasting PV devices and may offer a viable path for future research and development into more affordable, large-scale perovskite PV modules [51]. Also, Qatar Environment and Energy Research Institute (QEERI) scientists are combining both experiments and numerical simulations to explore this novel material. Research teams are partnering to optimize solar technologies for hot climates like Qatar, achieving over 20% efficiency in silicon and perovskite solar cells [52].

The literature review highlights that ensuring satisfactory visual environments is crucial for occupants' well-being and productivity. While several studies have explored the benefits of BIPVs in other regions with similar climates, few have focused specifically on Qatar's unique environmental conditions. Still, despite the increasing use of photovoltaic panels in modern architectural designs in Qatar, there's limited literature on evaluating the visual comfort of occupants in buildings with STSW. Therefore, this study investigates ST-PSCs tailored to Qatar's climate, using daylighting analysis to assess visual comfort parameters. This will be done by exploring the primary design factors WWR and VLT in visual comfort analysis. Fig. 3 shows the selection of the research topic in the region of Qatar.

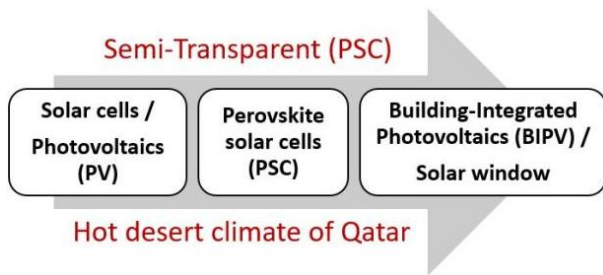


Figure 3. Schematic representation for the research topic selection of integrating ST- PSC into the BIPV window within the Qatar region

3. Research Methodology

The existing literature provides a robust framework for the proposed study, emphasizing specific visual comfort metrics to evaluate semi-transparent perovskite solar cells (ST-PSCs) within the context of Qatar's built environment. To carry out this evaluation, the study will simulate a single-room office model in Doha, incorporating a solar window on the building's south façade. The model will be developed using Rhino 8 (2023), and the parametric capabilities of the Grasshopper 1.0 plugin will facilitate flexible design iterations without requiring advanced scripting knowledge [53]. The parametric setup will allow the testing of different configurations of Window-to-Wall Ratios (WWR) and Visible Light Transmittance (VLT) which are central to optimizing STPW performance. Environmental performance simulations will be executed through Ladybug 1.6.0 and Honeybee 1.6.0, which integrate Qatar's meteorological data and interface with the Radiance engine to perform detailed visual comfort analyses that ensure accuracy in reflecting the unique environmental conditions of the region [54]. A grid-based daylighting model, utilizing Honeybee and guided by the Useful Daylight Illuminance (UDI) thresholds, will be applied to adjust the façade's transparency in response to varying daylight levels on a work surface positioned at 85 cm above the floor, consistent with methodologies from previous research [55]. Hence, the use of the selected parametric modeling and simulation tools allows for visual representation of data which can be shared effectively with stakeholders to translate findings into actionable recommendations. Later, to enhance the applicability of the results, findings will be benchmarked against related studies in the literature. This approach ensures that results are contextualized within the broader research landscape. Fig. 4 outlines the research design flowchart.

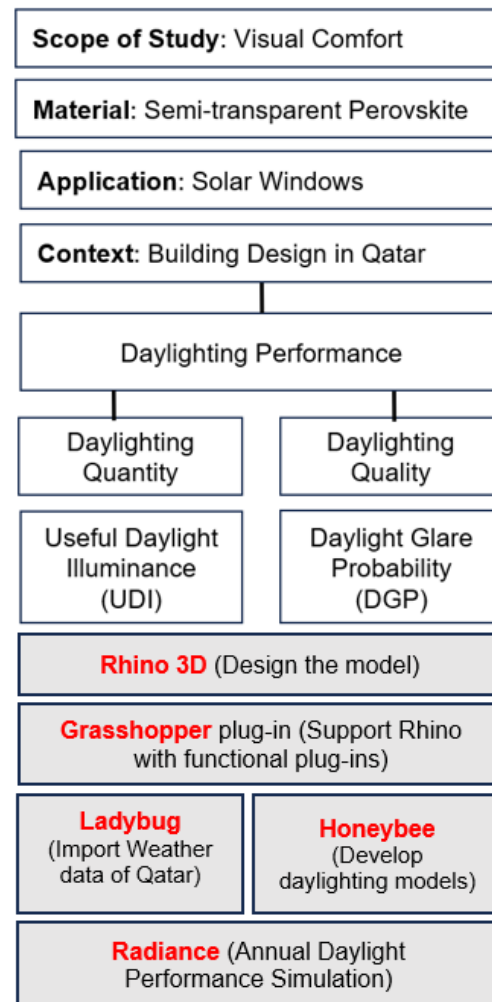


Figure 4. Research Methodology Flowchart

3.1. Case Study: Office Prototype

To evaluate the visual comfort parameters of the semi-transparent perovskite solar windows (ST-PSWs), annual climate-based daylighting metrics were utilized to assess daylighting performance. These metrics were compared with a reference model under various sky conditions and external illumination levels. The Useful Daylight Illuminance (UDI) threshold was set between 100 and 2000 lux to identify discomfort glare and potential heat gains effectively. In addition to UDI, the Daylight Glare Probability (DGP) metric was employed to assess the risk of glare within the indoor space. Fig. 5 illustrates the model parameters used in this study. Fig. 6 shows visual light metrics integral to the study.

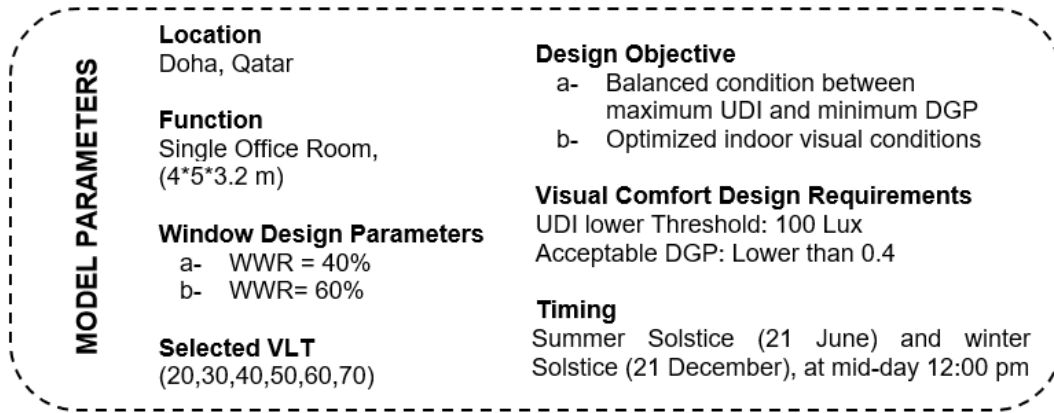


Figure 5. The model parameters applied in this study

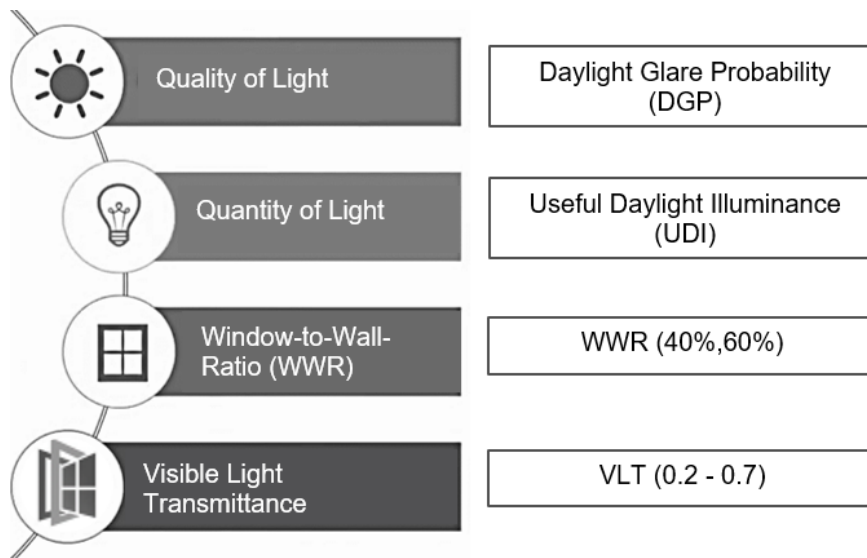


Figure 6. The parameters of visual light metrics for building design used in the study

The study will employ a series of simulations on a proposed model representing typical office spaces in Qatar, following the outlined procedures:

1. **Initial Modeling Setup:** Two distinct office room geometries were created using Rhino 8, depicting the installation of semi-transparent perovskite solar windows (ST-PSW) with two different Window-to-Wall Ratios (WWR). The first model features a WWR of 40%, reflecting the typical average for office buildings in Qatar. In comparison, the second model incorporates a WWR of 60%, designed to assess whether this increase improves visual comfort. Both models are oriented towards the south façade to maximize balanced daylight exposure throughout the day. The room dimensions are 4.00 × 5.00 meters, with a ceiling height of 3.2 meters, and they are free from external shading from nearby buildings (refer to Fig. 7).
2. **Simulation Development:** The models will be further developed using the Honeybee 1.6.0 plugin for Grasshopper. Location and weather data will be set

3. **Window Properties Definition:** Several ST-PSW samples with different Visible Light Transmittance (VLT) values ranging from 0.2 to 0.7 will be defined and applied to the window surfaces.
4. **Daylighting Control:** The advanced grid-based daylighting simulation mode in Honeybee, based on the Useful Daylight Illuminance (UDI) thresholds, will adjust the skin layers according to the light levels measured on an elevated task area situated 85 cm above the floor.
5. **Daylight Simulations:** Radiance will be used to run daylight simulations, calculating UDI and Daylight Glare Probability (DGP) for each model configuration.
6. **Determination of Optimal VLT:** The optimal VLT values will be identified, ensuring that the selected configuration delivers visual comfort with sufficient useful daylight illuminance.

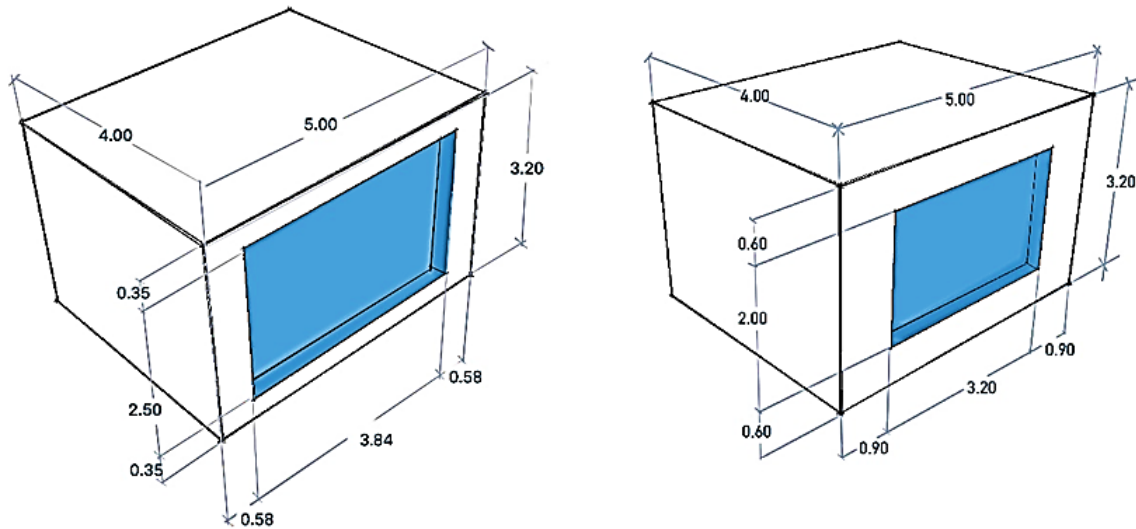


Figure 7. Office model utilizing ST-PSW with: a) WWR=40%, b) WWR=60%

Table 1 references visual comfort performance metrics applied in this study. It outlines qualitative and quantitative parameters, including daylight Glare Probability (DGP) and functional daylight illumination (UDI), which are crucial for assessing glare risk and overall daylighting comfort. Meanwhile, Table 2 presents the reflection coefficient percentages for the office materials used, which directly influence key simulation settings such as ambient bounces, divisions, and resolution. These values are fundamental for ensuring simulation accuracy. The ambient accuracy parameter typically ranges from 0.1 to 1, with lower values signifying greater precision. For this research, Honeybee’s definition of daylight simulation quality has been set to medium to balance computational efficiency and simulation detail.

Table 1. The visual comfort performance reference employed in this research

Analysis Method	Parameter	Performance Indicator
Qualitative	DGP	1- 0.35< imperceptible glare
		2- 0.35-0.40 perceptible glare
		3- 0.4-0.45 disturbing glare
		4- >0.45 intolerable glare
Quantitative	UDI	1- 100 lux < (dark area)
		2- 100 – 2000 lux (comfortable)
		3- At least 50% of the time >2000 lux (too bright)

Table 2. Simulation parameter settings employed in this research

Parameters for Radiance	Value
Ambient sampling	200
Ambient accuracy	0.15
Ambient divisions	1500
Ambient bounces	4
Ambient resolution	400

3.2. Daylighting Simulations

3.2.1. Useful Daylight Illuminance (UDI)

The study will analyze light distribution using the UDI parameter, which measures the proportion of time daylight illuminance is within the ideal range of 100-2000 lux. Values below 100 lux require artificial lighting, while values above 2000 lux can cause glare. The results will show the average UDI range, highlighting the integration's performance enhancement.

3.2.2. Daylight Glare Probability (DGP)

Daylight glare will be investigated as an indicator of daylight quality, focusing on its reduction. The analysis will utilize the DGP metric to pinpoint discomfort glare alongside the UDI analysis during the winter and summer solstices on December 21 and June 21, respectively. These dates are considered critical periods, with the most crucial time to control glare being midday (noon). The performance indicators used were previously outlined in Table 1.

4. Results Analysis

For the 40% Window-to-Wall Ratio (WWR) on June 21 at 12:00 PM, the simulations showed that varying the Visible Light Transmittance (VLT) levels directly impacted glare and daylighting performance. A VLT of 0.2 resulted in the lowest Daylight Glare Probability (DGP) at 0.19, suggesting excellent glare control in summer. However, the lower light transmission meant that artificial lighting might be needed in areas farthest from the window for tasks requiring detailed visual attention. As the VLT increased to 0.3, the DGP rose slightly to 0.24, remaining below the perceptible glare threshold. At the same time, daylight penetration improved, reducing the need for artificial lighting in most areas of the room. At higher VLT levels of 0.6 and 0.7, the DGP values increased to 0.32 and 0.34, respectively, nearing the disturbing glare threshold, yet the rooms benefited from ample daylight, making artificial lighting largely unnecessary.

In contrast, on December 21 at 12:00 PM, the DGP values increased across all VLT levels, indicating that glare management became more challenging during winter. A VLT of 0.2 yielded a DGP of 0.25, still within acceptable limits, though daylight levels were reduced due to lower light transmission and lower sun angles in winter. As the VLT increased to 0.3, the DGP rose to 0.30, approaching perceptible glare levels but still providing an acceptable balance between glare control and daylight penetration. At VLT levels of 0.6 and 0.7, glare became a significant issue, with DGP values reaching 0.43 and 0.47, respectively, indicating disturbing to intolerable glare. These results suggest that in winter, while higher VLT values offer better daylighting, they also result in excessive glare, making a VLT of 0.4 the most suitable choice for maintaining year-round visual comfort.

Overall, for a 40% WWR, the findings indicate that lower VLT levels (0.2-0.4) provide better glare control, particularly in winter, but may necessitate additional artificial lighting to ensure adequate daylighting in certain parts of the room. Higher VLT levels, while increasing daylight penetration and reducing the need for artificial lighting, pose a greater risk of glare, especially in winter.

Thus, a balance must be struck between adequate daylighting and visual comfort, with a VLT of 0.4 emerging as the optimal choice for year-round comfort in typical office spaces in Qatar. See Fig. 8.

For the 60% WWR, the summer solstice results on June 21 at 12:00 PM revealed a similar pattern, with lower VLT values offering better glare control but less daylight. A VLT of 0.2 resulted in a DGP of 0.21, effectively minimizing glare. However, reduced daylight levels meant that artificial lighting might still be necessary for detailed tasks in some regions of the room. As the VLT increased to 0.3, the DGP rose to 0.25, providing a balanced solution with sufficient daylight penetration and acceptable glare levels, making it suitable for most occupants during summer. However, at VLT levels of 0.6 and 0.7, the DGP increased to 0.35 and 0.38, indicating that glare became more noticeable, though daylight levels were significantly higher, minimizing the need for artificial lighting.

The larger window size made glare control more challenging during the winter solstice on December 21 at 12:00 PM. At a VLT of 0.2, the DGP was 0.27, indicating manageable glare levels, but again, daylight levels were lower, especially in the far reaches of the room, necessitating additional lighting. A VLT of 0.3 offered a good balance between daylight penetration and glare control, with a DGP of 0.30, which remained within acceptable limits. However, at VLT levels of 0.6 and 0.7, the DGP increased significantly to 0.43 and 0.56, respectively, crossing into the disturbing to intolerable glare range. This indicates that more oversized windows provide more daylight but also increase glare risk, especially during winter when the sun's lower angle exacerbates glare problems.

Thus, for a 60% WWR, the study suggests that lower VLT values, particularly around 0.3, provide the best balance between adequate daylighting and visual comfort, while higher VLT values, though beneficial for daylighting, pose significant glare challenges. Glare management becomes a key concern in winter, with more oversized windows requiring lower VLT values to maintain comfort. A VLT of 0.3 is recommended for more oversized windows to minimize glare while allowing for sufficient daylight in typical office spaces. See Fig. 9.

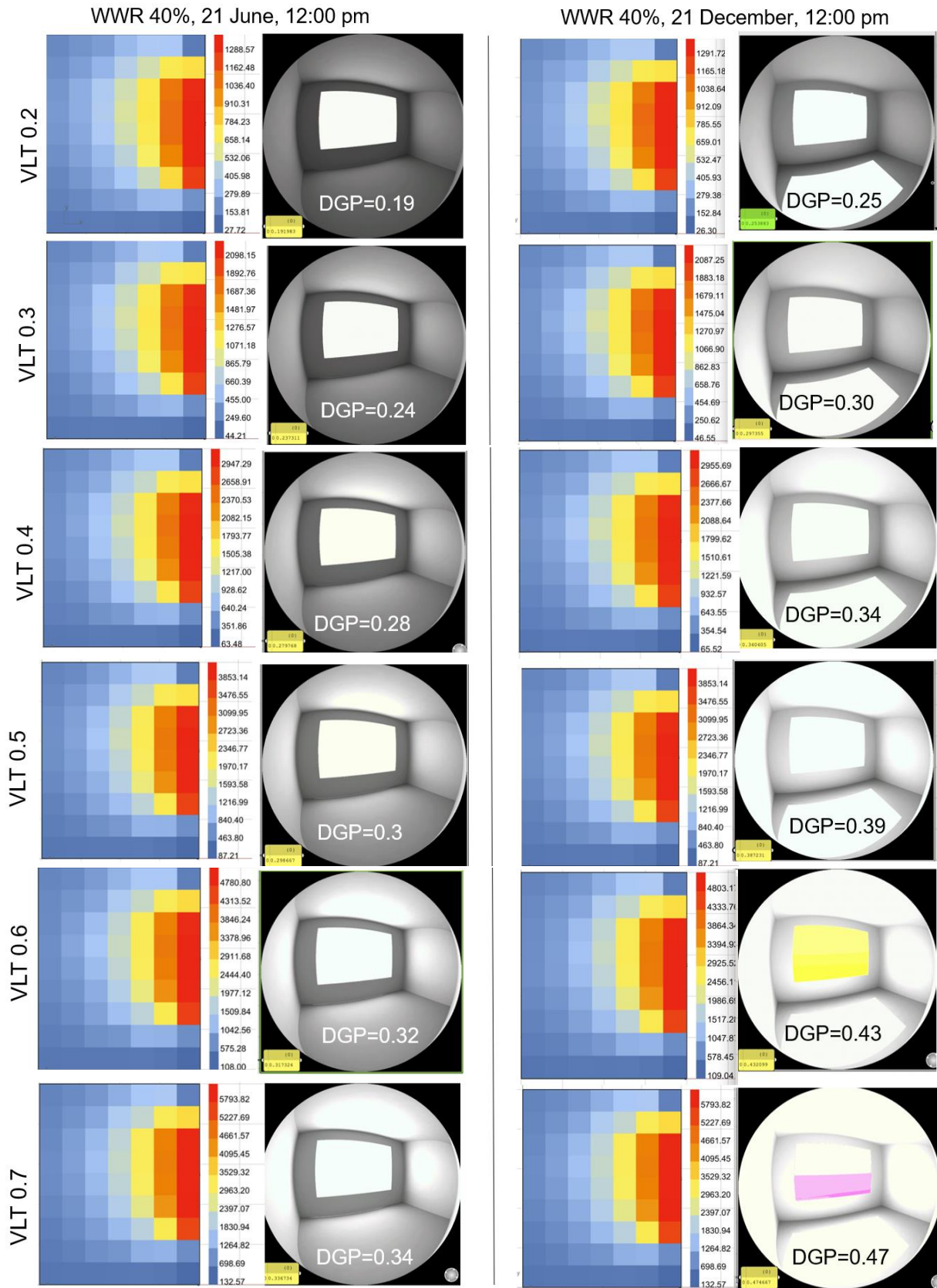


Figure 8. UDI heat map and DGP results for ST-PSW with VLT (0.2-0.7) and 40% WWR in summer and winter solstice

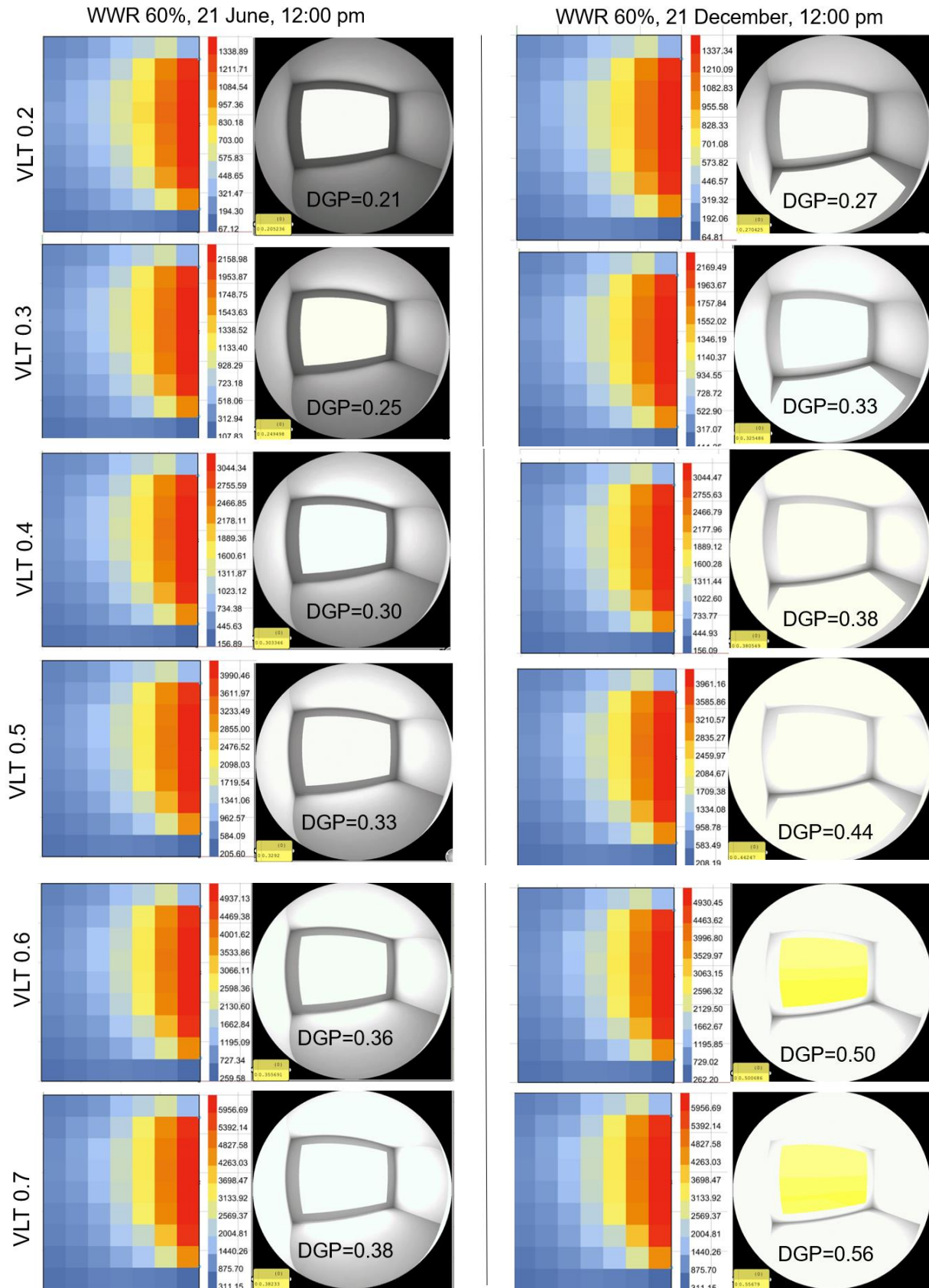


Figure 9. UDI heat map and DGP results for ST-PSW with VLT (0.2-0.7) and 60% WWR in summer and winter solstice

Fig. 10 compares the Useful Daylight Illuminance (UDI) and Daylight Glare Probability (DGP) across different VLT values and Window-to-Wall Ratios (WWR) for both summer and winter conditions. The results show that higher VLT values (0.6 and 0.7) provide more daylight, as reflected in higher UDI values, particularly during summer, but also increase the risk of glare. In contrast, lower VLT values (0.2 and 0.3) offer better glare control, especially in winter. However, they reduce daylight penetration, which could necessitate artificial lighting in some room regions, particularly during winter when daylight availability is already limited.

For a 40% WWR, a VLT of 0.4 provides the best balance between daylight and glare control. UDI levels ensure sufficient daylight for most tasks while keeping DGP levels within comfortable limits year-round. For a 60% WWR,

however, the optimal VLT value shifts to 0.3, as the larger window size exacerbates glare issues, particularly in winter when higher VLT values result in disturbing or intolerable glare. In summer, higher VLT values provide excellent daylighting but pose a greater risk of glare, particularly for occupants near the window.

Fig.10 mainly illustrates the trade-off between daylight availability and glare control, with more oversized windows requiring lower VLT values to maintain visual comfort. While higher VLT values enhance daylighting, they come at the cost of increased glare, particularly during winter. As such, carefully consider both VLT and WWR are essential to ensure a comfortable visual environment in office spaces, with VLT values around 0.3-0.4 recommended for most configurations to balance daylighting and glare control.

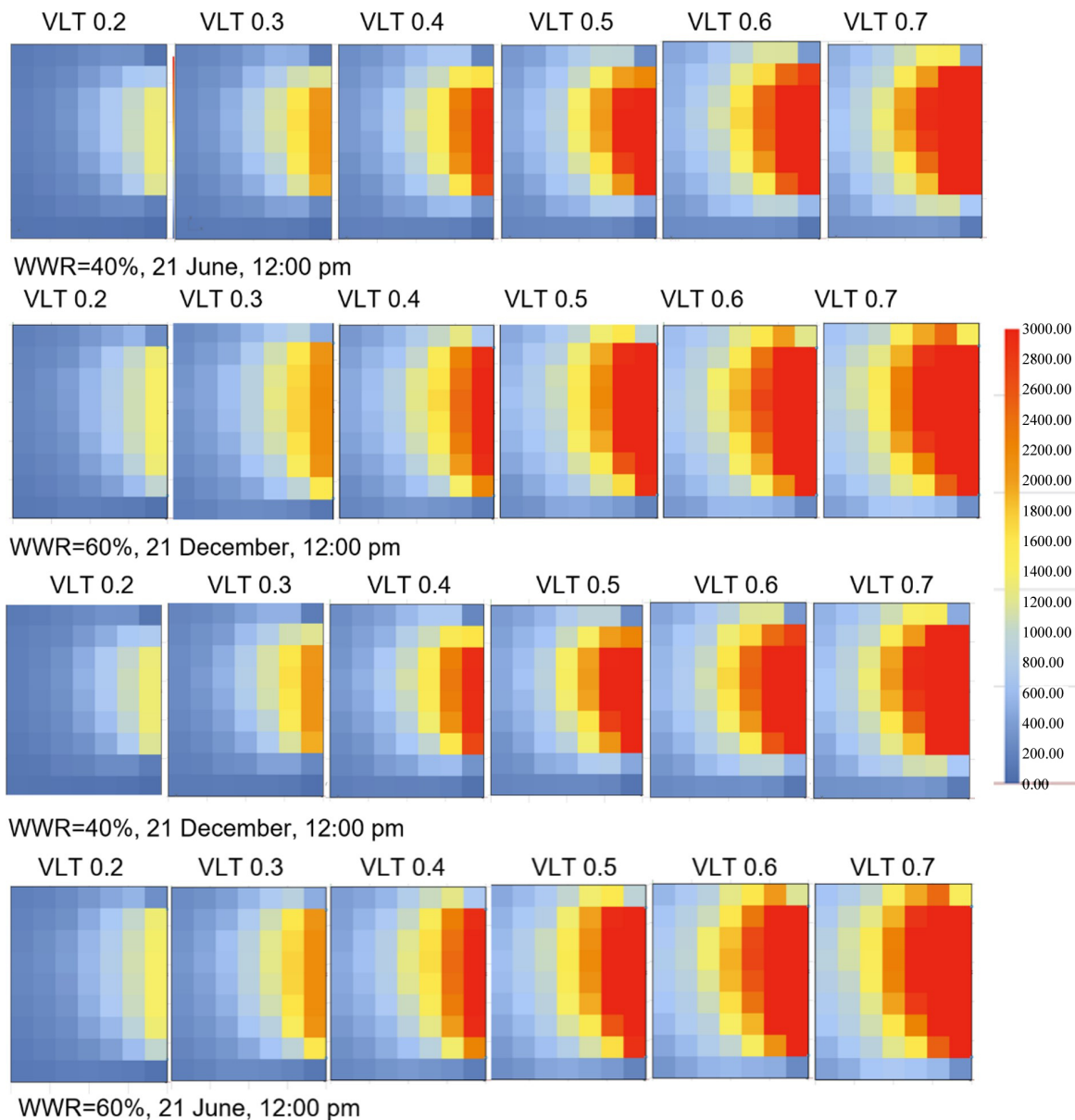


Figure 10. Comparison of UDI heat map with a fixed legend for the average UDI (0-3000 lux) for the VLT values (0.2-0.7), a. (40% WWR, Summer solstice), b. (40% WWR, Summer solstice), c. (60% WWR, Summer solstice), d. (60% WWR, Summer Solstice)

5. Discussion

This paper focuses on integrating semi-transparent perovskite solar windows into building designs and their impact on visual comfort and energy efficiency in Qatar. The results indicate that the change in the design parameters, such as the level of VLT and WWR, significantly impacts daylighting and glare control inside office spaces. For example, while VLT increases the distribution of natural light, reducing the dependency on artificial lighting, this is usually paid back with increased glare potential, especially during winter. These results align with previous studies suggesting that daylight performance optimization emanates from a balance between light transmission and glare control for improved occupant comfort and energy savings [2], [16].

Among the various design configurations, this study finds that a WWR of 60%, with VLT = 0.3, is optimal in ensuring year-round visual comfort within Qatar's hot desert climatic context by sustaining Useful Daylight Illuminance with adequate glare control. For a building with a 40% WWR, it is recommended that a VLT value of 0.4 is used to strike an appropriate balance between daylight availability and glare control. However, supplementary artificial lighting may still be required for tasks requiring high resolution in spaces positioned out of reach from the window, whereby sunlight angles are not sufficiently high during winter months, causing daylight availability levels to be low [1], [8]. Until recently, windows were considered to have no significant role in the passive solar heating and cooling of buildings. These recommendations align with studies about BIPV that emphasize window-to-wall ratio optimization for thermal and visual performances [12], [18].

The above study points out the critical insights of the trade-off between daylight penetration and glare. Higher VLT values, though decent for natural lighting, cause higher values of DGP, especially during winters. For example, a VLT of 0.7 at a WWR of 60% gives intolerable glare during winter, with DGP exceeding the acceptable threshold limits [10]. This finding underlines the importance of incorporating shading devices or intelligent technologies to moderate glare in higher VLT and larger window areas. On the other hand, this research opens new doors for future design guidelines that can take full advantage of integrating automated shading systems capable of dynamic adjustment to solar conditions, as demonstrated in recent studies concerning adaptive façades.

Therefore, this study would have a significant bearing on sustainable architecture practice. ST-PSWs are a promising avenue for reducing energy consumption through improved natural lighting, thereby adding to Qatar's Renewable Energy Goals. However, total dividends from these technologies can only be realized provided the building design makes an informed choice in the selection or trade-off between VLT, WWR, and shading solutions to assure optimum visual comfort throughout the year [19],[21]. The

result of this study aligns with Qatar's sustainability goals. It supports the development of architectural practices for hot desert climates by providing practical guidelines for future ST-PSW integrations in projects.

This study also underlines the necessity of further research on developing design strategies to optimally integrate semi-transparent solar windows with shading devices in terms of performance for different transparency levels. Additional simulations are necessary to show how shading systems can effectively reduce glare and maintain higher daylight in climates with extreme seasonal sunlight variations. These would be very important in enhancing visual comfort and minimizing the reliance on electricity in buildings in Qatar due to increasing concerns about sustainability in building design and operation.

Where the interaction between glazing properties and other types of climatic conditions, such as hot temperatures and dust, is concentrated, studies should also be conducted in the future. For instance, durability problems regarding ST-PSWs in the extreme desert environment of Qatar should be researched more theoretically [3], [26], which is another direction of investigation. Such technologies could go even further toward energy efficiency through active changes in lighting and shading based on real-time environmental data, with further ancillary benefits relative to additional improvements in occupants' well-being. Thirdly, performance monitoring of ST-PSW over a long period in the real world may provide valuable data on optimizing their design and application in big building projects.

The research ends with the fact that, at this moment, it adds to the knowledge based on sustainable building design, ever-enlarging, and provides practical guidelines for integrating ST-PSWs into Qatar's urban fabric. This presented study paves the way for developing visually comfortable, energy-efficient buildings in a hot desert climate by balancing daylighting, glare control, and energy efficiency.

6. Conclusions

This paper discussed the development of integrated semi-transparent perovskite solar windows in building design to optimally balance visual comfort with daylighting performance and energy efficiency in Qatar. The key findings highlighted in this paper indicate that VLT and WWR are two crucial design parameters of ST-PSWs, which play an essential role in the distribution of daylight and glare control in buildings. Their study identified that a 60% WWR with 0.3 VLT is optimum for comfort in all seasons because it provides adequate UDI, minimizes the need for artificial lighting, and controls glare. For buildings with 0.4 VLT, they recommended a 40% WWR; however, even this may require some artificial lighting during winter months. These principles, while derived for Qatar's conditions, are highly transferable to

other regions with similar high solar exposure such as the middle east, northern Africa and arid zones in the southern United States. Furthermore, these findings confirm the previous researchers' works that daylight penetration might be essential. Still, its balance against glare management in the future will be tricky and sensitive to achieve comfortable indoor environments in hot desert cities like Qatar.

The results of this study help update the field of sustainable architecture and assess the possibility of integrating renewable energy technologies into building design. With a focus on ST-PSWs, this research outlines Qatar's renewable energy goals through practical design guidelines that balance visual comfort, energy saving, and sustainability. Optimum VLT and WWR combinations enable the architects and engineers to draw valuable inferences on how ST-PSWs can be integrated into office spaces effectively, thus enabling reduced energy consumption and improvement in the well-being of occupants. The study further closes a gap in the literature for Qatar's specific climatic condition and adds to the local perspective on the potential of ST-PSWs in desert environments.

The findings also support global sustainability and energy efficiency goals with benefits having far-reaching implications, extending beyond Qatar to other regions with similar climates, where ST-PSWs can help achieve net-zero energy objectives. Additionally, the study highlights the critical balance between daylight access and glare control, which is a challenge shared globally in the building industry. In this way the paper provides valuable insights that can inspire global applications of ST-PSWs and inform sustainable architectural practices worldwide.

In this paper, some limiting factors must be identified. While the simulations have been beneficial, the dynamic effects of shading devices or other adaptive technologies that could further increase visual comfort are not considered. Further research should include these variables to refine the findings and develop more comprehensive design strategies. Second, the long-term performance and durability of ST-PSWs have not yet been tested under Qatar's extreme climatic conditions and may require further monitoring and field studies to ensure reliability over time for these technologies. Another limitation is that the results rely on simulations and do not have real-world validation, which may affect the general applicability.

This research study contributes significantly to understanding how ST-PSWs may be integrated into the design of buildings in Qatar while addressing several of the limitations identified in this research. Additional advanced strategies, like thermal coatings and self-cleaning surfaces that repel dust, could be developed to optimize the performance of ST-PSWs and contribute towards more sustainable, energy-efficient, visually comfortable building environments in Qatar and other hot desert climates based on some of the leading findings of this research study.

Acknowledgements

We would like to convey our sincere gratitude to everyone who helped and contributed to completing this research paper. They have been beneficial and supportive in making this study possible.

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