Evaluating Window View Quality of Building-Integrated Photovoltaic Using Immersive Virtual Reality

by

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A thesis

presented to the University of Waterloo

in fulfillment of the

thesis requirement for the degree of

Doctor of Philosophy

in

Civil Engineering

Waterloo, Ontario, Canada, 2025

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Author's Declaration

I hereby declare that I am the sole author of this thesis. This is a true copy of the thesis, including any required final revisions, as accepted by my examiners.

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Abstract

Building-Integrated Photovoltaic (BIPV) windows have gained increasing attention due to their onsite energy generating capability and possibility of reducing operational carbon, but their impact on occupants' view experience in terms of view clarity and privacy has not been addressed. This research addresses this gap by assessing how various design approaches of mono- and poly-crystalline Silicon BIPV windows impact occupant satisfaction using a human-centric perspective, based on the combination of subjective experience and objective BIPV windows performance analysis.

For this purpose, an immersive virtual reality (IVR) test was developed which enabled more than 70 participants to assess BIPV window views in a virtual office setting. The IVR approach is a scalable process for early-stage assessment of the façade which is particularly useful in environments where the development of a physical prototyping is expensive, time-consuming or not possible.

Solar cell size and visible light transmittance (TVIS) were varied to assess trade-offs among view clarity, privacy, and overall satisfaction. The selected by the participants configurations were further analyzed in terms of annual daylighting performance and PV energy generation. This included performance metrics as daylight autonomy and glare probability, as well as potential generated electricity (kwh/m^2/year), to paint a picture of how user-preferred BIPV configurations will perform in the context of energy generation and daylighting.

The results show a trend where BIPV configurations with increasing TVIS were preferred overall by participants for better view clarity and higher overall satisfaction, even if their view privacy was slightly compromised. A BIPV window with full size cells and TVIS = 0.48 was found to be the preferential configuration, providing both view satisfaction and an acceptable PV output.

This scalable, repeatable, and cost-effective approach enables researchers and designers to simulate and assess occupant perception of BIPV window views, offering valuable insights for

sustainable, occupant-centered façade design. These insights aim to guide improvements in BIPV window design, ensuring a balance between maximizing energy generation while maintaining window functionality and occupant comfort.

Keywords: Building-Integrated Photovoltaic (BIPV) Windows, Window View Quality, Immersive Virtual Reality (IVR), Occupant Satisfaction, View Clarity, View Privacy, Sustainable Façade Design, Energy Generation, Daylighting Performance

Acknowledgements

Pursuing this PhD has been a long and meaningful journey, marked by both ups and downs. I'm truly thankful to everyone who helped and supported me along the way.

First and foremost, I want to express my deepest gratitude to my supervisors, Dr. Joyce Kim and Dr. Costa Kapsis, for their invaluable guidance, continuous encouragement, and insightful advice throughout my doctoral research. Their mentorship has shaped both my academic path and personal development.

I am also thankful to the members of my PhD committee, Prof. Carl T. Haas, Dr. David Correa, Dr. Amy Li, and Dr. Won Hee Ko, for their time, constructive feedback, and valuable contributions to my work. A very special thanks to Dr. Mohammad Araji, without his generous guidance and continued support, this research would not have been possible.

I gratefully acknowledge the financial support provided through the NSERC Discovery Grant. This support made this research possible.

I want to thank Professor Amy Li for generously providing access to the SPER Environmental Quality Datalogger, which supported the environmental measurements in this study.

My heartfelt appreciation goes to my family: Mahdi, Fariba, Sana, Fatima, and Onee, for their endless love, patience, and belief in me. Their presence has been a constant source of strength and inspiration.

Last but certainly not least, to my dear friends: thank you for your encouragement, your presence, and the memories we created together. Your friendship has brought light to this journey, and I will always be grateful.

Dedication

To my dear parents, Fariba and Mahdi, whose infinite love and sacrifices have brightened my path, and to my little Dara and Delara, my most cherished aspirations and delights.

And after them, this is for all that shapes who I am:

For my "*diar-e asheghi*", my lonely, sad Iran, a homeland that won't vanish like dust in the wind. From the Aras River to the Persian Gulf, from Sistan's wild mountains to Ilam's quiet hills, every culture, language, and dream keeps this land alive, strong in its wrinkled, steady arms. Every town and story-filled hill is mine, just as I belong to it: whole, unbreakable, at peace.

And finally, to the people of Iran, proud, kind, and impossibly brave, your courage is our soul. From the silent strength of mothers to the fearless screams of girls, you are the beating heart of freedom, dignity, and joy.

In the hope of a free Iran.

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List of Symbols

A_i	Surface area of each visible window fragment (m^2)
A_{lim}	Surface area of visible view (m^2)
A_{ref}	Total reference view area used in comparisons (m^2)
DA	Daylight Autonomy, percentage of occupied hours above threshold lux
DGP	Daylight Glare Probability, index of glare risk
DOP	Degree of Privacy, proportion of interior view hidden from external observers
E_{AC}	Normalized AC energy generation per unit façade area $\left(\frac{kWh}{m^2}\right)$
EL	Electric loss factor, accounts for inverter and system losses
EOV	Effective Outside View, weighted measure of view access and clarity
F_q	Quality factors indicating desirability of different view components (e.g., sky, greenery)
F_v	Quality factors for privacy, binary indicating whether outsiders can see inside (0 or 1)
I	Plane-of-array (POA) solar irradiance (W/m^2)
$\mathrm{I_{ref}}$	Reference irradiance (1000 W/m^2)
OF	Openness Factor, the ratio of the holes (spaces between yarns or fibers) to the overall surface of the shading fabric
$\mathrm{P_{BIPV}}$	Normalized BIPV power output per unit surface area (W/m^2)
PF	Packing Factor, fraction of façade area covered by opaque photovoltaic cells

sDA300/50%	Spatial Daylight Autonomy, % of floor area with ≥300 lux for ≥50% of occupied hours
sDG	Spatial Disturbing Glare, % of floor area experiencing glare
t_a	Ambient dry bulb temperature (℃)
t_{cell}	Operating PV cell temperature (℃)
t_{ref}	Reference cell temperature (25 °C)
TVIS	Visible light Transmittance of Glazing/BIPV window configurations
Umet	Wind speed from meteorological data (m/s)
V_{access}	Sub-component of VQI representing access to views
$V_{clarity}$	Sub-component of VQI representing clarity of views
$V_{content}$	Sub-component of VQI representing content of views
VCI	View Clarity Index, quantifies clarity through shading or glazing
VOO	View-Out Quality, ratio of visible desirable view components to total reference view
VQI	View Quality Index, composite of view content, access, and clarity
a	Empirical coefficient for BIPV temperature model (–2.85 ℃)
b	Empirical coefficient for BIPV temperature model [–0.0351 (m/s) $^{-1}$]
Δt	Constant temperature difference for double-glazed BIPV systems (9℃)
η	Electrical efficiency of BIPV module
$\mu_{P,mp}$	Temperature coefficient of BIPV module maximum power (1/℃)
Ω_{FOV}	Overall solid angle of the human visual field, ~78° cone half-angle (sr)

$TVIS_{n-n}$	Normal-Normal Light Transmittance Factor
$TVIS_{n-dif}$	Normal-Diffuse Light Transmittance Factor
θ_i	Angle between the window normal and the line of sight from the eye to the fragment, in degrees (°)

Chapter 1

Introduction

1.1 Background and Relevance

Buildings account for about 36% of the world's energy consumption, and nearly 40% of the world's energy-related CO_2 equivalent emissions, according to the International Energy Agency (IEA) [1]. This makes the building industry one of the leading contributors to global warming, necessitating a drastic reduction in energy use and emissions within the industry. The Paris Agreement recognized the need to limit the global temperature increase to below 2°C above pre-industrial levels (as far as possible), and decarbonize the building sector [2]. Similarly, the UN's Sustainable Development Goal 11 aims to "*make cities and human settlements inclusive, safe, resilient, and sustainable*", therefore highlighting the relevance of energy-efficient buildings [3].

Renewable energy, particularly solar photovoltaic (PV), plays a crucial role in achieving these global sustainable targets. Compared to other renewable technologies such as wind or biomass, and to conventional fossil-fuel-based power generation, solar energy can be more cost-competitive, and it is scalable, from small residential buildings to large commercial and utility-scale ones, so it assumes a major role among sustainable building solutions. The national and international stage has highlighted the attempts and efforts towards energy-efficient buildings, with recent projections show that more work is needed to meet the 2050 net-zero emissions goals. An international challenge like this is also an opportunity for creative solutions[1], [3]. Among renewable solutions, photovoltaic (PV) technologies appear to be a promising pathway, mainly because of their abundance and adaptability [4]. PV technologies are very scalable, and therefore, it is a great technology for use in a broad range of sizes and applications. These include small-scale systems, such as rooftop PV for individual homes, medium-scale PV technologies for commercial/retail buildings, and large-scale ground-mounted PV farms supplying electricity to the grid.

This scalability makes PV a flexible technology to meet diverse energy requirements. The PV modules are generally mounted in open space where they can directly receive sunlight to generate maximum power [5]. On the other hand, utility-scale or ground-mounted PV cannot be installed easily in an urban environment with high population density [6]. Building-integrated photovoltaic (BIPV) windows are an innovative solution for space-constrained and on-site energy generation in urban scenarios. They are particularly applicable to buildings with a high window-to-wall ratio (WWR). BIPV windows (Figures 1 and 2) are increasingly promoted as one of the best solutions for incorporating solar energy into buildings because, though they generate electricity, they allow light to pass into the building. Meanwhile, they also decrease the amount of solar heat gain through partial covering which can be beneficial in cooling-dominated seasons. However, in heating-dominated seasons such as winter, reduced solar heat gain may increase heating demand. This trade-off highlights the importance of balancing solar control and passive heat gains, and suggests that BIPV design strategies should be adapted to climate, orientation, and seasonal energy needs. BIPV windows reduce a building's total operational energy consumption and carbon emissions [7]. Unlike standard solar panels, BIPV windows can vary in size, color, and transparency, allowing for customizable options that can match the building's exterior. Thus, BIPV windows can provide both a renewable energy generation function and aesthetic appeal, thereby harmonizing the façade of a building [8].

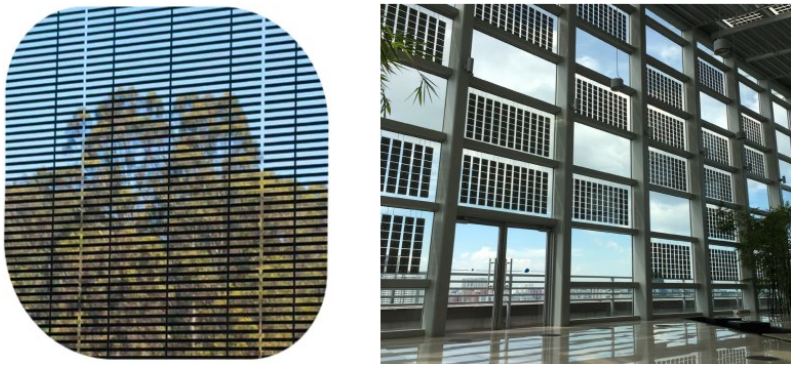


Figure 1. Examples of Commercial Building-Integrated Photovoltaic (BIPV) Window Products [9]

Although BIPV windows offer significant benefits in terms of on-site renewable generation, façade integration, and architectural flexibility, their adoption is not without challenges. In practice, the design and deployment of BIPV windows involve complex trade-offs. Among the most critical is the balance between maximizing energy generation and daylight performance on the one hand, and maintaining essential qualities of windows, such as view clarity, privacy, and overall occupant satisfaction, on the other. This trade-off aligns with the emerging global consensus on how window view quality should be assessed. Satisfying the growing demand for solar energy generation usually leads to an increase in the coverage of solar cells on glazing windows. Greater cell percentage coverage can produce more electricity, but often at the expense of view clarity, daylight distribution, and overall perceived view quality. Despite extensive research into the energy performance [10-18], architectural integration [12-13], [19-26] and optoelectronic properties [22], [27-34] of BIPV windows, limited attention has been paid to understanding and quantifying the effect of different BIPV configurations in satisfaction of occupants to their window views [24], [35].

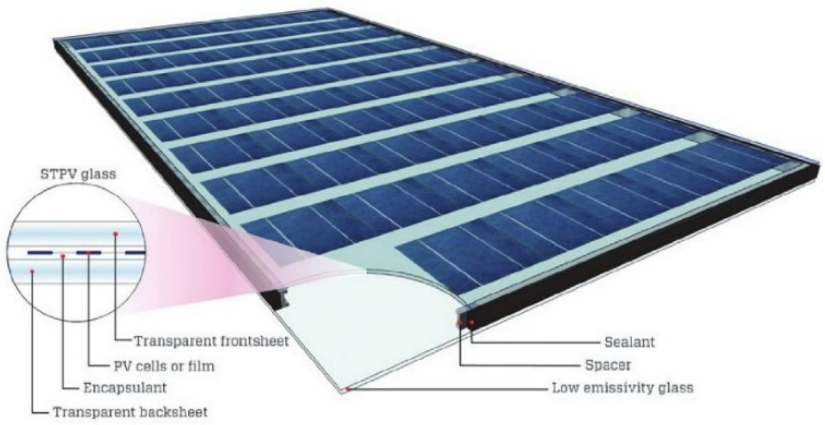


Figure 2. Schematic of double-glazed BIPV window integrating mono- or poly-crystalline Silicon cells [36].

This study responds to the need for understanding how various BIPV window configurations influence both energy generation and occupants' satisfaction with their window views.The study will introduce a method using immersive virtual reality (IVR) to explore crucial BIPV window design parameters, such as solar cell size and packing factor (PF). This scalable, repeatable and cost-effective method aims to simulate and assess occupant satisfaction of BIPV window views, potentially offering valuable insights for sustainable, human-centred façade design. These insights aim to guide improvements in BIPV window design, ensuring a balance between energy generation and maintaining window quality.

By addressing how different BIPV window configurations influence view clarity, privacy, and overall occupant satisfaction, alongside their daylighting and energy generation performance, this research bridges the gap between sustainable building technologies and occupant-centred design. The findings are expected to contribute to the development of BIPV solutions that both support environmental goals and enhance occupant well-being. This work lays the groundwork for innovative, human-centred façade designs that align sustainability with user comfort**.**

1.2 Research Problem

A critical knowledge gap exists regarding the impact of BIPV windows on occupant satisfaction. This problem persists due to the absence of a validated and scalable methodology to evaluate occupant view satisfaction during the design phase. To resolve these issues, this research addresses the following core questions:

- Is IVR a method that can be used to assess occupants' satisfaction for BIPV window views?
- In what ways do different BIPV window configurations influence occupant satisfaction with view clarity and perceived privacy, and are these effects moderated by demographic factors such as gender?

- How do BIPV window configurations, that occupants rated most satisfactory in terms of view clarity, privacy, and overall satisfaction, perform in terms of energy generation and daylighting effectiveness?

1.3 Research Objective

The primary objective of this research is to evaluate how different configurations of BIPV windows affect occupants' satisfaction with view clarity, privacy, and overall satisfaction, while also assessing their daylighting and electricity generation performance. This research aims to fill the existing gap by adopting a human-centred approach that integrates subjective occupant experiences with objective environmental and energy metrics, supporting the development of holistic, sustainable façade solutions. To address the research problem, this study is organized around three interrelated objectives:

1. **Feasibility of IVR for Evaluating BIPV Window Views:** This objective i examines whether immersive virtual reality (IVR) can serve as a reliable method for assessing occupant satisfaction with BIPV window views. The focus is on testing how realistic, engaging, and technically robust the simulations are in capturing user experiences.
    - Evaluate realism, spatial presence, and user involvement in IVR.
    - Identify technical/methodological challenges (e.g., latency, fidelity, fatigue) and propose improvements.
2. **Occupant Satisfaction with BIPV Window View Clarity and Privacy:** This objective investigates how BIPV design parameters (solar cell size and visible light transmittance, *TVIS*) affect satisfaction with view clarity, privacy, and overall impressions. It also explores potential demographic differences in these perceptions.
    - Identify configurations that maximize occupant satisfaction.
    - Examine relationships among clarity, privacy, and overall satisfaction.
    - Test whether demographic factors (e.g., gender) influence satisfaction ratings.

3. **Energy and Daylighting Analysis of Preferred BIPV Configurations:** This objective analyzes how occupant-preferred BIPV window configurations perform in terms of energy generation, daylight quality, and glare control. Using validated daylight simulation tools, the study quantifies performance to balance human-centered and sustainable outcomes.
    - Estimate annual energy output of selected configurations.
    - Assess daylight metrics such as Spatial Daylight Autonomy (sDA) and Daylight Glare Probability (DGP).
    - Identify trade-offs and synergies between visual comfort, satisfaction, and energy yield (kWh/m^2/year).

Together, these objectives aim to inform BIPV window design strategies that align human-centered preferences with sustainable performance targets.

1.4 Organization of the Thesis

The thesis is structured to present each component of the research in a coherent and focused manner. Chapter 2 reviews existing literature on BIPV in sustainable architecture, factors influencing window view quality, IVR applications, and identifies the key research gaps. Chapter 3 evaluates IVR as a methodological tool to support future assessment of occupant satisfaction of BIPV window views, including evaluation and refinement of the simulation environment, interaction design, and presence questionnaire. Chapter 4 investigates occupant satisfaction with different BIPV configurations, focusing on perceived view clarity, privacy, and overall satisfaction. Chapter 5 assesses the energy generation and daylighting performance of the most preferred configurations, identifying optimal design trade-offs. Finally, Chapter 6 synthesizes key findings, discusses implications for design and practice, outlines study limitations, and recommends directions for future research.

Chapter 2

Literature Review

2.1 BIPV in Sustainable Architecture

BIPV represents an innovative renewable solar energy technology that offers sustainable solutions for onsite energy generation while maintaining aesthetic appeal. BIPV technology seamlessly incorporates photovoltaics in building envelope elements, including windows, roofs, balconies, skylights, and facades, transforming buildings into active power generators [27], [35], [37].

The evolution of BIPV technologies has been marked by significant advancements in PV cell efficiencies, colours and window materials and design (Figure 3). Early BIPV technologies primarily utilized mono- and poly-crystalline Silicon cells, but recent developments have seen the emergence of thin-film technologies, including amorphous silicon (a-Si), cadmium telluride (CdTe), and copper indium gallium selenide (CIGS), offering greater design flexibility and aesthetic options [27], [35].The advent of PV technologies like organic (OPVs), dye-sensitized (DSSC) and perovskite photovoltaics (PSC) further expands the possibilities for architectural integration [27], [35].

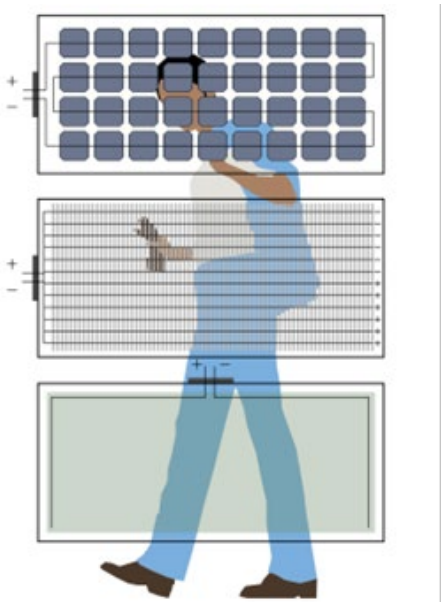


Figure 3. Crystalline-Si (Top); a-Si (Mid) and CdTe (Bottom) BIPV Modules for window applications (Courtesy of: S. Eskandar)

BIPV windows present various aesthetic and functional design choices, from fully transparent to semi-transparent and translucent products and colour-neutral to coloured glass systems [8]. BIPV windows offer a dual advantage when used in new construction or retrofitted into pre-existing façades [38]. Firstly, they produce on-site renewable electricity. Secondly, if designed properly, they can improve building efficiency and architectural design, notably by acting as solar shading devices [8], enhance occupant visual and thermal comfort and reduce building cooling loads [39]. BIPV windows can significantly address the limited space issue for traditional solar installations by generating onsite electricity for buildings [6]. The most advantageous applications of BIPV windows are in buildings with high WWR, where extensive glazing often leads to excessive solar heat gains and glare. In such contexts, occupants frequently keep shading devices closed for prolonged periods, which reduces their access to daylight and view and increases reliance on artificial lighting [40]. By integrating photovoltaic

cells, BIPV windows not only generate renewable electricity but also act as partial shading devices. This approach has the potential to reduce glare and overheating while still admitting sufficient natural light. As a result, occupants can keep shades open for longer periods, maintain window view access, and rely less on artificial lighting during daytime hours, lowering both energy consumption and operational costs. Mono- and poly-crystalline Si cells remain the dominant commercial technology due to their higher efficiency, market availability, and cost-effectiveness whereas emerging alternatives remain limited in deployment. Their integration into windows poses unique challenges for daylight, visual comfort, and view quality because they fully block transmitted light and partially obstruct outdoor views [28]. This underlines the need for further research on how occupants perceive and evaluate window views through mono- and poly-crystalline Si BIPV windows.

Incorporating BIPV windows into architectural designs has witnessed significant attention in recent years, leading to many research studies investigating their energy performance and efficiency. Martín-Chivelet et al. [35] highlighted how building-specific conditions like partial shading and reflections can influence BIPV efficiency, while Zhang et al. pointed out that BIPV windows might not always match the energy efficiency of traditional solar panels due to the inherent compromise of being transparent [27]. However, they also suggested that with proper design considerations, BIPV can significantly offset a building's energy consumption. Kuhn et al. further emphasized the potential of BIPV, particularly in urban environments [10]. They suggested that even though BIPVs might sometimes show reduced efficiency compared to standalone PV systems, their integration benefits in urban settings, resulting in long-term energy savings, make them an increasingly popular choice for sustainable building design. Kapsis et al. demonstrated that BIPV modules with TVIS = 30% provided sufficient daylight (sDA300lx/50% = 1.0; sDA500lx/50% = 0.6) while keeping glare intolerable for less than 5% of the year. A three-section façade design further improved annual daylight autonomy by 7–16 percentage points, showing how BIPV can balance electricity generation and daylight access in commercial façades [13]. The study highlighted the importance of optimal WWR for different façade orientations to maximize energy production, underscoring the potential of BIPV

windows to enhance the overall energy efficiency of buildings. Bonomo et al. examined the optical properties of BIPV windows, examining their effects on energy savings and architectural aesthetics [37]. Their categorization of BIPV based on opacity revealed significant insights into how light is transmitted, affecting interior aesthetics and energy performance. As Scognamiglio observed, there remains a knowledge gap concerning the visual performance of BIPV, particularly in understanding BIPV as a constituent of building envelope systems [20]. Finally, Markvart et al. [31] explored user perceptions of transparent thin-film BIPV windows, highlighting the importance of design patterns in influencing daylight perceptions. In their study, Markvart et al. discovered that people generally preferred horizontal striped patterns on transparent thin-film PV windows over square patterns. Interestingly, they found that people's preference wasn't directly linked to the room's brightness. For example, brighter rooms were preferred in one test, but in another, dimmer rooms were favoured. The key finding was that designs that maintain a clear horizontal view and don't overly alter the natural light are more likely to be preferred when it comes to BIPV windows. To the author's knowledge, Markvart et al. is the only BIPV window study that incorporates human subject feedback on view quality for BIPV windows. Appendix A summarizes previous studies on BIPV windows, which focus on their energy performance, savings potential, thermal and visual comfort, and technological advancements.

Energy performance and saving potential: The literature confirms that BIPV windows offer significant energy performance benefits and savings potential. For instance, Chow et al. determined that a solar cell transmittance between 0.45 and 0.55 optimizes energy savings by balancing daylight utilization with a reduction in air-conditioning load in offices [41]. Similarly, An et al. [42] reported that installing amorphous-silicon BIPV windows reduced the combined heating and cooling loads by 18.2% compared to conventional double clear glass windows (baseline scenario). In their case-study office building in Daegu, which was strongly cooling-dominant (≈93% of the annual load), most of this reduction came from lowering cooling demand, while heating demand occasionally increased depending on the operating conditions. Moreover, Do et al. [43] demonstrated that BIPV windows could cut annual energy

consumption by approximately 12–21% and peak cooling demand by 14–26%. These savings were achieved mainly through the shading effect of the PV cells, which reduced solar heat gains and cooling loads, and through daylight-dimming controls that lowered lighting energy use. Meanwhile, the best window design under semi-arid climates could lead to maximum energy savings of 60% for south-facing double-glazing PV modules [44]. Peng et al. [45] found that southeast-facing BIPV windows optimize energy performance, with south and southwest orientations being most effective for power generation in specific locations like Berkeley, California. Finally, regarding economic feasibility, Ng and Mithraratne [46] established that commercially available semi-transparent BIPV modules are financially viable alternatives to traditional windows, offering payback periods between 1.1 to 13.1 years.

Thermal and Visual Comfort: Various studies also address critical aspects of thermal and visual comfort. Yoon et al. [47] noted that BIPV windows, with their lower SHGC, reduce solar heat gains. This reduction in unwanted heat gain helps prevent overheating, thereby improving thermal comfort in occupied spaces. However, as Ghosh et al. [48] observed, when TVIS remains relatively high, (50–70%), the increased daylight penetration, although beneficial for illumination, can also introduce glare, which creates challenges for visual comfort, particularly in hot desert climates. As mentioned before, Markvart et al. [31] explored preferences for patterns and shading technologies, found that striped patterns improved view quality.

Technological and Material Advances: Advancements in BIPV window materials and technologies have explored perovskite-based films, semi-transparent silicon modules, dye-sensitized cells, and urban integration strategies, each addressing daylighting, energy efficiency, or comfort trade-offs. Cannavale et al. [49] discussed the benefits of Perovskite-based PV windows, which act as solar control films while generating electricity effectively reducing glare and improving Useful Daylight Illuminance (UDI). Kapsis et al. [13] examined a BIPV module with 30% visible light transmittance that integrates well with the outer layer of a double-glazed window, ensuring adequate daylight and acceptable glare levels year-round. Chung et al. [50] highlighted the potential of DSSC windows, which can achieve significant energy savings with 13% Power Conversion Efficiency (PCE) and 30% Visible Light

Transmittance (TVIS). Lastly, Chen et al. [51] discussed the impact of BIPV windows on urban environments, noting that they can reduce building cooling loads and urban canyon air temperatures, with effects varying based on the canyon aspect ratio and window coverage. Mesloub et al. [44] cited limitations in certain technologies, where integration of BIPV windows with internal light shelves using a-Si modules did not meet visual comfort standards due to low transmittance but achieved substantial energy savings.

To summarize, the literature confirms that BIPV windows enhance energy performance, providing savings in heating, cooling, and lighting while also contributing to onsite renewable electricity generation. Studies further highlight their role in supporting thermal and visual comfort, reducing solar gains and glare while maintaining adequate light transmission. However, despite these advantages, most existing research has focused on the energy performance of BIPV façades, with limited attention to their impact on occupants' perceived view quality. In particular, no studies have examined how design features such as solar cell size or visible light transmittance influence clarity, privacy, or overall satisfaction using human-centred evaluation methods. Moreover, many existing studies rely heavily on simulation-based approaches, and even when experimental methods are applied, they often exclude human participants and serve mainly to validate models. This oversight is notable given windows' crucial role in connecting individuals to their external environment, enhancing well-being and productivity. Key design factors, such as cell arrangement, warrant closer examination for their impact on perception of the outside world. Ultimately, balancing energy generation with the quality of visual experience is essential.

2.2 Window View Quality (Content, Clarity, Access and Privacy)

Windows serve an essential function in providing a view of the outside world and allowing daylight into indoor spaces [52]. According to the field study by Dogrusoy and Tureyen [33], most office workers preferred walls with windows that provided the most significant window area due to broad views and natural light [33]. Further supporting the importance of visual windows, Jiang et al. [53] introduced the concept of a “visual window,” defined as a window

that provides occupants with a clear connection to the outdoors through natural views and daylight access. Compared to either windowless rooms or windows with obstructed views (e.g., facing a blank wall), visual windows were found to improve comfort, reduce stress, and lessen fatigue. In line with this, other studies have confirmed that windows offering meaningful views, not just glazing, enhance health and well-being by linking occupants with outdoor environments. Windows with views not only bring natural light into indoor spaces but also contribute to improving the occupants' health and well-being [54], [55]. Research consistently shows that windows with views improve emotional states [56], cognitive performance [56], [57] environmental satisfaction [58], and reduce discomfort [59]. For example, Benfield et al. [54] conducted a field study, revealing that students' classroom performance improved when rooms had windows with views, suggesting that such environments enhance learning by providing visual relief and mental stimulation. Similarly, Norwood et al. [55] found that lessons in nature-based outdoor classrooms improved attention and on-task behavior among students.

Window views offer benefits across diverse building contexts. Ko et al. [56] found that windows providing a view of nature positively influenced occupant emotion, thermal comfort, and cognitive performance (particularly working memory and concentration). Additionally, Boubekri et al. [57] observed that window views, particularly those with natural elements, reduce mental fatigue and enhance concentration. Windows with natural views have proven effective in hospital settings as well. Research by Ulrich et al. [60], from a study conducted nearly a decade (1972-1981) on hospital patients showed that those with access to natural views through windows experienced more effective recovery than those in windowless rooms. Further research by, Ulrich et al. [61] found that recovery in natural settings occurs faster and is deeper, leading to improved emotional states and physiological health, suggesting the importance of incorporating natural views in building design for well-being and productivity. This supports the framing by Ko et al. [62] , who defined window view quality through three primary components: content, access, and clarity. This structure is now widely endorsed across disciplines as the standard foundation for view-related studies.

Window views can also positively impact property values [63], [64], [65]. Baranzini and Schaerer [63] found that environmental amenities (e.g., natural and built features of the landscape) visible from windows can greatly influence rental prices. For instance, properties with water views can result in rent premiums of up to 57%. Similarly, Damigos and Anyfantis [64] mentioned properties in Athens with views of green spaces or the sea can increase in value by up to 50%, while those with undesirable views might decrease by 25%. Moreover, Turan et al. [66] introduced metrics for assessing view potential in office spaces, finding that high view access correlates with a 6% rent premium. These metrics, Minimum View Potential (MVP) and Spatial View Access (sVA), help evaluate and enhance view access in urban office designs.

Research on window view quality has progressed from early frameworks to more recent indices that quantify specific dimensions (see Appendix B). Markus [67] and Hill & Markus [68] developed some of the frameworks, emphasizing that windows must provide an adequate amount of visual information and that mesh or slat shading can degrade clarity when visual information is lost. Hellinga [69] later introduced the D&V analysis method, a broader framework integrating daylight and view quality, which highlights view content, layering, and diversity as critical factors.

Moreover, indices were developed to measure particular aspects of view. The index for view clarity, the View Clarity Index (VCI), was introduced by Konstantzos et al.[70]. It is specifically designed to evaluate the clarity of view through fabric shades, using the shade's openness factor (OF) and normal visible light transmittance ($TVIS$):

$$VCI = 1.43 \times (OF)^{0.48} + 0.64 \times \left(\frac{OF}{TVIS}\right)^{1.1} - 0.22 \quad (1)$$

Flamant et al. [71] later extended the VCI to incorporate material color and diffuse light transmittance, producing a more fabric-sensitive formula:

$$VCI = -0.461 \times e^{-66.6 \times TVIS_{n-n}} - 0.467 \times \left(\frac{TVIS_{n-dif}}{TVIS_{n-n}}\right)^{0.296} + 0.921 \quad (2)$$

Here, $TVIS_{n-n}$ represents the normal-normal light transmittance factor, while $TVIS_{n-dif}$ denotes the normal-diffuse light transmittance factor. The fabric-based extension

demonstrates how openness, color, and diffusion jointly affect clarity. While developed for shading fabrics, these principles are conceptually relevant to BIPV windows, even if the formula itself is not transferable to windows that integrate opaque photovoltaic cells.

The VCI is a dimensionless metric where higher values indicate clearer, less obstructed outdoor views, while lower values reflect reduced clarity due to shading or material properties. For example, VCI values above ~0.8 typically correspond to high-quality views, whereas values below ~0.3 indicate severely obstructed or degraded view [70], [71].

Subsequent indices expanded the scope. Konstantzos & Tzempelikos [72] introduced the effective outside view (EOV), integrating clarity with geometric factors, while Purup et al. [73] proposed metrics for View-Out Quality (VOO) and Degree of Privacy (DOP).

Konstantzos & Tzempelikos [72] formulated the EOV, which quantifies the connection to the outdoors, incorporating factors such as view amount and clarity through shading materials. The EOV is computed as follows, incorporating visual angle and clarity weighting for each window fragment:

$$\text{EOV} = \frac{1}{\Omega_{FOV}} \sum_i VCI_i \,.\, A_i \,.\, \frac{1-\cos\theta_i}{2} \qquad (3)$$

where: $\sum_i VCI_i$ Is the VCI for each window fragment, A_i is the area of each visible window fragment, θ_i is the angle between the window normal and the line of sight to each visible window fragment (e.g. the portion of the window view that remains unobstructed by shading or mullions) and, the Ω_{FOV} is the overall solid angle of the human visual field is approximated as a circular cone with a half-angle of 78 degrees.

However, the VCI, EOV, and View-Out Quality (VOO) / Degree of Privacy (DOP) formulas are not universally applicable, particularly in the context of BIPV windows using opaque solar cells. These models were developed primarily for transparent or semi-transparent systems and rely on parameters like visible light transmittance, openness factor, or continuous view geometry. In contrast, BIPV windows using opaque solar cells introduce binary visual obstruction through photovoltaic cell patterns that disrupt visual access in pixelated ways. As such, these indices

are limited in their ability to predict view quality or satisfaction in scenarios where no direct transmission occurs, and clarity must instead be evaluated through perceptual or immersive methods. For example, the VCI is specific to fabrics and may not extend well to window obstructions like frits and BIPV windows, or other non-fabric shading systems. On the other hand, EOV needs detailed data on window properties not always available in the early design stages.

Purup et al. [73] introduced computational models to assess window views by integrating various comfort aspects, including privacy and view quality, to inform design decisions better. Two metrics measured in this study were VOO/DOP.

$$\text{VOO (View-Out Quality)} = \frac{\sum(A_{lim} \cdot F_q)}{A_{ref}} \quad (4)$$

and

$$\text{DOP (Degree of Privacy)} = 1 - \frac{\sum(A_{lim} . F_v)}{A_{ref}} \quad (5)$$

They calculated the area of visible view (A_{lim}) and compared it to the total reference view area (A_{ref}). The visibility of various parts of the view was adjusted using quality factors (F_q) defined on a 0–1 scale to reflect the relative desirability of view components (e.g., F_q = 1 for sky or trees, F_q = 0.1 for roads or parking areas). For privacy, the quality factors (F_v) were binary (0 or 1), indicating whether specific view segments might allow pedestrians to see into the room. This metric calculated the proportion of the room visible from outside, adjusted by binary quality factors, to provide a privacy score.

Wasilewski and Andersen [74] introduced a perceptually grounded approach to evaluating view visibility through façade systems by applying the HDR-VDP-3 vision model. Their method simulates human visual perception to estimate the degree to which visible contrast in outdoor scenes is preserved under different shading conditions. While their study focused on fabric shades, venetian blinds, and electrochromic glazing, not BIPV, this modeling approach offers promising potential for future research on BIPV façades using opaque solar cells, where

complex geometries may cause similar patterns of visual obstructions despite high daylight performance.

Mardaljevic [75] introduced the view lumen concept to integrate view quality into daylight analysis by focusing on aperture-based daylight modelling. Kim et al. [76] developed the Seemo tool, which aids early design evaluations of window view satisfaction in residential buildings.

Finally, building on previous studies of window view quality which typically assessed individual aspects like clarity or access, Ko et al. [62] have established a comprehensive window view quality assessment framework that quantifies the aspects of view impacting occupant satisfaction. This framework integrates three primary variables: view content, view access, and view clarity, each derived from a broad review of daylighting standards, green certification systems, and scientific studies. To mathematically evaluate the overall view quality, they propose the view quality index (VQI), which combines these variables in a formula that encapsulates their interdependencies:

$$VQI = V_{content} \times V_{access} \times V_{clarity} \quad (6)$$

Here, $V_{content}$, V_{access}, $V_{clarity}$ are measures of the view's content, the degree of access to the view, and the clarity of the view, respectively. Each component is scored based on specific criteria detailed in their framework, capturing a comprehensive evaluation of view quality from multiple dimensions.

Appendix B provide an overview of previous studies that have assessed window view quality. Across these works, the metrics are typically grouped into four factors: **content, access, clarity,** and **privacy,** each of which strongly influences occupant satisfaction. However, it is important to note that most of these equations (e.g., VCI, EOV, VOO/DOP, VQI) were developed for transparent or semi-transparent glazing and shading systems. They rely on parameters such as visible light transmittance, openness factor, or continuous view geometry, which do not apply to mono- and poly-crystalline BIPV windows. in these BIPV windows, visual obstruction occurs in a binary, patterned manner (through solar cell layouts) rather than

through uniform light transmission. This limits the direct transferability of these indices, underscoring the need for perceptual or immersive evaluation methods tailored to BIPV window configurations.

Content: Many researchers have explored the content of window views, with studies examining preferences for natural versus urban scenes. For example, Aries et al. [59] investigated how the content of window views impacts office workers' well-being, showing that natural elements greatly improve psychological comfort and reduce discomfort. This aligns with the study by Lin et al. [77], who assessed occupants' preferences for views, including natural landscapes over built environments. Zanon et al. [78] developed a visual quality index that proved useful in the design process of residential buildings by focusing on nature and urban features, dynamic features, and horizontal stratification. Overall, the variables studied related to window view content include nature and urban features [77], horizontal stratification (e.g., ground, landscape, sky layers) [79], content distance [78], and dynamic features (movement) [80].

Access: Previous studies assessing window view access focused on various geometric variables such as view angles [76], percentage of glazing area [81], window distance [70], viewing direction [72], and percentage of window view area in the visual field (PWV) [82]. Ko et al. [82] introduced the "View Access Index," which evaluates how the geometric variables of windows, such as size and placement, affect access to views and occupant satisfaction. These variables were experimentally tested through human subject experiments using virtual reality, which indicated that glazing area, window distance, and viewing direction are critical predictors for occupant satisfaction regarding view access.

Clarity: Compared to contents and access, fewer studies have explored window view clarity. Konstantzos et al. [70] developed the VCI, which considers shade openness and visible light transmittance. Based on previous studies, two variables can impact window view clarity: window design (e.g., frame, mullions) [83], and glazing and shading materials [78]. The general focus of most studies has been on clear windows without considering different materials,

except for the work by Flor et al. [84], who assessed window view clarity using Ethylene Tetrafluoroethylene (ETFE) cushions, a material that presented unique optical properties relevant to clarity characteristics. Flamant et al. [71] emphasized that standardized clarity metrics may not fully capture perceived view quality. Their study demonstrated that fabrics with similar transmittance values can result in distinct clarity perceptions due to differences in color, luminance, and lighting conditions. While EN 14501 [85] provides classification criteria for visual contact through solar shading fabrics based on normal-normal and normal-diffuse transmittance, such metrics are inapplicable to BIPV windows using opaque solar cells, which lack meaningful transmission through their active areas. This highlights the need to develop alternative clarity frameworks tailored to perceptual obstruction in systems like BIPV.

Privacy: Privacy is often overlooked in many studies. However, the works by Purup et al. [73] and Kim et al. [76] highlight its importance, showing that privacy concerns depend strongly on view content and access. Purup et al. [73] integrated privacy into their models by weighting only those view segments where outsiders could look into the room, while distant or nature-oriented views posed no privacy risk. Similarly, Kim et al. [76] incorporated architectural and environmental factors into their Seemo tool, demonstrating how privacy and view quality must be considered together in early design evaluations.

Various experimental methodologies have been used to assess window view quality in previous studies, including field experiments, laboratory experiments, and VR experiments, with or without human subjects. These approaches offer distinct advantages, limitations, and insights into how window views affect occupants. Researchers like Dogrusoy and Tureyen [33] deployed field experiments to directly assess the impact of window types and view quality in real-world settings, typically in office environments. This approach is instrumental in understanding actual occupant responses in their daily environments. Yun et al. [86], for example, conducted lab experiments to simulate specific environmental conditions, such as luminance levels, to study discomfort glare from different window views. This controlled setting allows for precise manipulation of variables and measurement of specific responses.

VR simulates various viewing scenarios in a controlled yet immersive environment. Abd-AlHamid et al. [87] used VR to explore how different viewing locations within a simulated office affect perception and physiological responses. This method is valuable for studying the subjective and physiological impacts of views without requiring costly physical alterations; however, its limitations include restricted realism (e.g., challenges in replicating glare, luminance, or fine detail), potential motion sickness, and limited validation across all sensory aspects. While few studies (e.g., Abd-AlHamid et al. [87]) have directly applied VR to window view quality, related works by Flor et al. [84], Ko et al. [82], and Chamilothori et al. [88] demonstrate VR's growing role in evaluating clarity, and access, though further methodological validation is still needed.

In window view quality assessments, two main experimental methods are employed: human subject testing and formula-based evaluations. Human subject testing involves real-world experiences where participants assess views from various windows, providing subjective feedback on factors like satisfaction, as seen in studies by Dogrusoy and Tureyen [33] and Arie et al. [59]. Alternatively, formula-based assessments use equations like the VCI [70] and EOV [72] to objectively measure view clarity and connection to the outdoors, integrating variables like shade openness and visible light transmittance. Incorporating both human subjects and formula-based assessments allows for a holistic understanding of both the view satisfaction and practical aspects of window views, crucial for optimizing design for occupant satisfaction.

In conclusion, while a substantial body of research has explored view quality about content, access, clarity, and, to a lesser extent, privacy, most existing models have been developed for clear or semi-transparent glazing systems. Tools like VCI, EOV, DOP, and VQI were developed for transparent or semi-transparent materials and were not designed to evaluate the perceptual implications of binary visual obstruction found in BIPV windows integrating opaque solar cells. These systems challenge traditional assumptions by introducing binary occlusion, patterned geometry, and visual segmentation rather than uniform haze or transmittance. his challenge is not unique to BIPV: similar effects occur in shading and glazing systems that rely on discrete occluding elements. Horizontal blinds, for example, segment views into repetitive

slats, reducing continuity and masking fine details of the outdoor scene [74], [89]. Recent work on bird-safety glazing confirms the same principle, patterns of dots or stripes alter perceived clarity depending on their spacing, coverage, and orientation. In a VR-based evaluation, striped patterns were found to preserve clarity more effectively than dot matrices, but clarity declined consistently as overall coverage increased [90]. These parallels indicate that the perceptual mechanisms identified for BIPV windows, loss of continuity, segmentation of view content, and dependence on occlude geometry, can be generalized to a broader family of façade systems. They also underscore why clarity models based on haze or uniform transmittance (e.g., EN 14501 classes, VCI) remain poorly suited for patterned systems, highlighting the need for perceptually grounded approaches. This creates a clear research gap at the intersection of novel façade technologies and human-centered visual evaluation, a gap this thesis addresses using immersive VR-based clarity, privacy, and satisfaction assessments. Note that Khanie and Andersen [89] proposed a novel contrast-based framework for evaluating view quality through solar-control systems, using spatial features extracted from HDR luminance images. Although this methodology differs from the perceptual IVR approach, their findings reinforce the importance of human contrast sensitivity and scene legibility in view clarity evaluation, especially relevant for BIPV window configurations, where visibility is often obstructed or patterned. This gap suggests a need for targeted research to evaluate how BIPV windows affect occupant satisfaction, potentially altering factors such as light transmission and solar cell arrangements. In addition, the privacy aspect of window view quality, particularly in relation to the partially obstructive or selectively open characteristics of BIPV façades, has received little empirical attention. While studies have developed indexes for assessing view content, access and clarity, window view privacy has received minimal attention. Hence, further research is needed to explore the impact of privacy on window view quality assessment and its interaction with other assessment factors, ensuring a holistic understanding of occupants' view satisfaction with specific window materials and designs.

2.3 Immersive Virtual Reality in Window View Research

Virtual Reality (VR) is broadly defined by Coburn et al. [91] as adding a virtual scene in place of one or more actual senses. Freina & Ott [92] categorize VR into non-immersive and immersive. Non-immersive VR refers to a computer-based environment that can imitate locations in the real or made-up worlds, while Immersive VR (IVR) creates the perception of being physically present in a non-physical simulated world [92]. Due to its affordable and portable devices, IVR is gaining popularity in various fields of study, such as healthcare, education, science, and engineering. Recent studies have shown that well-designed virtual environments can approximate real-world settings in terms of spatial layout and visual appearance, particularly in relation to environmental perception and occupant feedback [93].

In a research context, IVR has successfully replicated expensive or high-risk field experiments [88], [94], [95]. IVR has been used as an effective tool in recent experiments to address the shortcomings and difficulties of performing field experiments. Field research may be challenging, especially in human-centric studies. Logistic restrictions, high prices, time restrictions, and issues manipulating variables and simulating real-world settings are some of the obstacles. The immersive nature of VR minimizes the experimental setting's perceived artificiality, as participants cannot see the physical setup or the experimenter. This isolation helps mitigate biases caused by behavioral changes in the presence of observers [98]. Moreover, compared to other simulated virtual environment methods, such as the use of photographs, 2- or 3-dimensional rendered images displayed on screens, or reduced-scale mock-ups, VR can make experiments feel more natural while allowing for greater control over various environmental factors [94]. As an example, VR can maintain consistent illuminance levels that mimic natural daylight conditions, which is a common challenge in window-based research [88], [99]. Rapid changes in visual stimuli within VR can decrease the time required to conduct experiments, offering researchers a broader range of settings and environmental conditions for replication [94], [95]. However, despite these advantages, few studies have specifically applied IVR to evaluate occupant perception of window views that are obstructed or fragmented by novel façade systems, such as those integrating shading layers or

photovoltaic technologies . Only a limited number of works, such as Flor et al. [84], who assessed ETFE façades, and no known studies have evaluated opaque or pattern-blocked photovoltaic window views using IVR.

Various studies summarized in Appendix B have explored numerous aspects of occupant comfort and environmental perception by using IVR. Chamilothori et al. [88] utilized IVR to assess the perception of daylit spaces, comparing real and virtual environments in terms of perceived pleasantness, interest, excitement, complexity, and satisfaction with the view. The findings indicated that IVR could offer a high level of perceptual accuracy for evaluating daylit spaces, thereby enriching our understanding of how natural light influences occupant satisfaction and spatial perception. Heydarian et al. [100] explored end-users' lighting preferences within office spaces through IVR, collecting data on human preferences and performance that could inform better building designs aimed at increasing user satisfaction and potentially reducing energy consumption. This study highlighted how tailored environmental settings can enhance occupant comfort and operational efficiency. As another example, Salamone et al. [101] investigated the effect of visual stimuli on personal thermal comfort perception by comparing feedback from participants exposed to real-world and virtual scenarios. This study used VR to assess personal thermal comfort and demonstrated how visual and environmental variables can affect occupants' thermal comfort perceptions. Finally, Alamirah et al. [112] reviewed studies spanning from 2012 to 2021 that used IVR to investigate occupant comfort and behavior in buildings. They mention IVR's utility in simulating and controlling environmental variables such as lighting, temperature, and acoustics to analyze their effects on occupant behavior and comfort. While IVR allows detailed and controlled experiments, challenges remain in replicating the full sensory complexity of real-world environments.

Several studies specifically addressed window view assessments, assessing how virtual representations of windows and views affect occupant satisfaction and perception. For instance, Moscoso et al. [102] investigated the impact of window size on spatial perception and satisfaction, revealing that larger windows enhance the perceived spaciousness and

satisfaction with the view amount, which is crucial for architectural design in high latitudes. Abd-Alhamid et al. [87] focused on the restorative benefits of various viewing positions within virtual environments, highlighting that proximity to windows can enhance perceived quality and psychological benefits, thereby influencing design strategies for window placement and orientation to optimize occupant well-being.

Recent years few studies have investigated the window view quality using VR. For example, Abd-Alhamid et al. [87] explored how the perception of window views changes with the observer's distance from the window, using VR to simulate views at close, middle, and far distances. Flor et al.'s study [84] used VR to investigate how ETFE-based double-skin façades affect occupant' perception of view clarity and satisfaction. Their findings demonstrated VR's utility in pre-construction evaluation of innovative façade materials that subtly alter visual transmission, although they did not address fully obstructive or patterned systems like photovoltaic modules. Ko et al.'s [82] study leveraged VR to assess the impact of window geometry on occupant satisfaction within office environments. It identifies key factors glazing area, distance to the window, and viewing direction as significant determinants of view satisfaction. This study is a noteworthy contribution to the field, highlighting the effectiveness of VR in exploring the nuanced effects of architectural design elements on indoor environmental quality. Finally, Abd-Alhamid et al. [81] explored how different window designs affect occupants' well-being in office settings, focusing on window size and layout. Utilizing VR, the research demonstrates that larger windows enhance view quality, stress recovery, and psychological well-being. Kojima et al. [103] developed a window view quality index to assess occupant satisfaction concerning view access, taking into account variables like window size, viewing distance, and direction. Their research found that certain geometric variables like WWR significantly influenced occupant satisfaction, contributing valuable insights for the design phase of buildings to enhance occupant comfort and satisfaction with window views. Wang and Munakata [104] deployed IVR to assess the impact of planning factors, such as the layout of buildings, inter-spaces, and surrounding trees, and the ratios of visual elements (sky view, buildings in a vertical front), on perceived oppressiveness in high-rise residential

environments. They found that increased sky ratios, wider separating distances between buildings, a staggered formation and additional floor number are influential factors in diminishing visual confinement. This work highlights the potential of immersive tools for evaluating spatial perception and justifies their use to evaluate the design of façades and urban configurations. All these studies consistently involved human subjects to validate their findings, reflecting the importance of direct human feedback in assessing the qualitative aspects of building design via IVR. The research varied in the specific attributes measured, ranging from psychological comfort and visual quality to physiological responses, highlighting the broad applicability of IVR in evaluating different dimensions of window view quality and its impact on human perception and well-being (see Appendix C). This collection of research illustrates that IVR is an indispensable tool in the field of IEQ, particularly for the detailed assessment of how window views can be optimized to improve both occupant well-being and building performance. However, most IVR-based studies have focused on clear or lightly filtered glazing systems. There remains a lack of research on how IVR can be used to evaluate window views that are obstructed, pixelated, or segmented by opaque shading elements. Kim et al. [93] empirically compared physical space, virtual reality, and digital image-based assessments of window view satisfaction. While VR and image-based methods proved valid for evaluating view content, privacy, and overall satisfaction, their ability to accurately simulate clarity particularly in scenarios involving glare, reflections, or near-field obstructions, was limited. The authors caution against using VR and IM for clarity evaluations, emphasizing the need for further methodological development when assessing visually obstructive façades or patterned glazing.

Despite these advantages, validation studies on VR's effectiveness for luminous environment research are limited and often focus on specific aspects, lacking comprehensive evaluations across subjective and objective measures [88], [100]. In terms of validating the VR immersive environment for luminous studies, some research, like that by Chamilothori et al. [88], has compared stereoscopic renderings against real environments on aspects like lighting impressions and views, finding no significant differences. However, not all studies calibrate VR

scenes with real-world photometric data [95], which is a crucial step for accurate comparisons. Further, when comparing performances in different lighting conditions, some studies have not directly contrasted identical conditions in both real and virtual setups, nor specified luminance or illuminance levels, factors known to impact performance [94], [105], [106], [107]. Validation studies are few and typically concentrate on a single aspect of the bright environment. To further verify VR's suitability for assessing any visual environment's lighting, a replication of the findings is necessary. Furthermore, the investigations either only included subjective assessments or did not include physical calibration of the VR material. Color, contrast, and detail are examples of visual quality criteria that have not yet been verified [108]. Cho et al. [109] demonstrated that variations in VR display fidelity, such as motion type, media representation, and scene rendering, can significantly influence occupants' perception of window views and associated physiological responses. Their findings, along with identified limitations in realism and luminance handling, highlight the need for consistent calibration and control of visual parameters when using immersive environments to evaluate perceptual responses to façade views. Moreover, few studies have assessed how IVR handles spatial fragmentation or patterned visual occlusion, conditions commonly introduced by façade-integrated systems such as fritted glazing [84].

Abd-Alhamid et al. [108] conducted a comprehensive study involving twenty participants to compare subjective and objective visual responses within both a virtual and a real office environment. Their study is important for understanding how VR can replicate real-world conditions, specifically regarding the visual quality of window views and the impact of lighting on spatial perception. The study finds no significant difference in visual performance and perceptions of lighting quality between the VR and real environments. This underscores VR’s growing credibility as a tool for visual perception studies, especially in domains where physical prototyping is impractical or where emerging façade systems require controlled yet flexible simulation environments. Abd-Alhamid et al.'s work signifies a key step in adopting VR for environmental psychology, architectural design, and lighting studies, offering a promising

alternative for researching the impact of visual quality and lighting on human perception and well-being.

However, despite the increasing use of IVR in architectural evaluation, there is still a lack of studies that specifically examine how opaque, fragmented, or patterned façade systems, such as crystalline-based BIPV windows, affect occupant perception of view clarity, privacy, and overall satisfaction within immersive environments. This presents a significant research gap at the intersection of emerging façade technologies and immersive perceptual assessment.

In conclusion, studies leveraging IVR have demonstrated mixed results regarding its reliability for assessing IEQ and window view quality. As shown in Appendix C, approximately 50% of the reviewed studies validate IVR's tool for IEQ studies by deploying comparative analyses, including real-world versus virtual environments assessments to measure parameters like environmental evaluations and user satisfaction. As shown in Appendix C, only 29% of the reviewed studies have validated IVR for assessing window view quality, highlighting a significant research gap. Key validation methods deployed include statistical analyses such as ANOVA [101], [110] and factor analysis [110] help understand how virtual environments mimic real settings. For instance, Kort et al. [110] found that while virtual environments could replicate some aspects of real environments, they lacked the ability to evoke full emotional responses, as evidenced by the absence of the arousal dimension in virtual settings. Additionally, tasks like size estimations and cognitive mapping were performed more accurately in real environments, indicating that virtual environments still do not fully match real-world settings' sensory and emotional fidelity. Despite these limitations, studies like Chen et al. [95] deployed correlation analyses to evaluate the congruence of VR with actual physical environments. Specifically focusing on lighting conditions, the study found that VR reproductions of lighting environments were highly consistent with real settings, delivering a more immersive and accurate experience compared to alternative digital media such as video and photographic reproductions. However, despite these notable efforts, the lack of validation across window quality assessment studies highlights the ongoing need for robust research to confirm the effectiveness of IVR. This gap highlights IVR’s potential as a cost-effective research

platform for exploring underexamined aspects of window view quality, especially clarity, privacy, and satisfaction in façade-integrated systems such as BIPV windows.

2.4 Summary of Identified Research Gaps

Building on the gaps identified in the literature, this thesis focuses on:

- **Human perception of BIPV windows:** While many studies investigate energy or daylight performance, little is known about how specific BIPV window configurations affect human perception, particularly view clarity, privacy, and overall satisfaction.
- **Design parameter influence:** There is limited empirical evidence on how variations in visible light transmittance (TVIS) and solar cell size influence perceived clarity, privacy, and satisfaction with BIPV windows.
- **Disconnect between performance metrics and user experience:** Existing analyses often emphasize energy yield and daylight metrics (e.g., daylight autonomy, glare probability) but rarely connect these results to occupant-preferred configurations, leaving a gap between simulation-based performance evaluations and human-centered outcomes.

This thesis will bridge these gaps by combining immersive VR-based perception studies with environmental simulation to evaluate how BIPV design affects both occupant experience and building performance. In light of these gaps, the next chapter presents a methodological approach developed to evaluate how visually obstructive photovoltaic window configurations influence occupant perception of clarity, privacy, and overall satisfaction, leveraging immersive VR to address limitations in current view quality assessment tools.

Chapter 3

Immersive Virtual Reality for Evaluating BIPV Window Views: A Feasibility Study

3.1 Introduction

This chapter focuses specifically on evaluating the feasibility of using IVR as part of a research method for studying occupant satisfaction with BIPV window views. While Chapters 1 and 2 outlined the dual challenges of optimizing BIPV windows for both energy performance and view satisfaction, this chapter addresses the methodological question of how those perceptual qualities can be evaluated effectively. Traditional methods of assessing window view quality, such as physical mock-ups or field studies, offer realism but are often constrained by high costs, long project timelines, and limited experimental control. These constraints limit the ability to efficiently explore and compare multiple BIPV configurations in early-stage design.

In response, Immersive Virtual Reality (IVR) has been introduced as an alternative. It enables researchers to simulate architectural environments with high spatial precision, allowing participants to engage with virtual window views in a way that closely mimics real-world experience. IVR also offers repeatability, ensuring consistent test conditions across all participants, and flexible design manipulation, which avoids the need for costly physical prototypes. These attributes make it well-suited tool for early-stage architectural evaluation.

However, the use of IVR as a research method for studying view clarity, view privacy, and overall satisfaction in BIPV window designs remains underexplored. Questions persist regarding the perceptual realism of the simulated environments, the extent to which users feel immersed or "present", and whether such experiences can yield data reliable enough to guide design decisions in real-world practice.

This chapter aims to evaluate whether IVR is a methodologically sound tool for capturing these perceptual dimensions in the context of BIPV window research. It begins by reviewing relevant literature on IVR in architectural evaluation, outlines the structure and software behind the IVR

simulations used in this study, and presents the evaluation framework adopted to assess user experience, immersion, and engagement. Through this, the chapter lays the foundation for the broader IVR-based evaluations carried out in later stages of the thesis.

3.1.1 Objective

The aim of this study is to evaluate the feasibility of using IVR as part of a methodological setup for future assessments of occupant view satisfaction with BIPV window configurations. This chapter addresses the methodological question of whether IVR environments can produce realistic, reliable, and immersive simulations suitable for human-subject evaluations in window view research.

This part of the study was conducted in two phases:

- A pilot test with 10 participants to explore initial user experience, identify technical limitations, and implement improvements in rendering, navigation, lighting consistency, and interface clarity.
- An evaluation study with 20 participants, using a clear window configuration as the baseline scenario. Participants assessed their IVR experience using a standardized Presence Questionnaire measuring three core dimensions: realness, spatial presence, and involvement.

The overarching goal is to determine whether IVR simulations are perceptually credible and methodologically reliable enough to be used in subsequent human subject evaluation of BIPV window view satisfaction.

Study Questions

- Can IVR simulate window views with sufficient realism and perceptual fidelity to support occupant evaluation of view quality?
- Does the IVR environment enable participants to experience a high sense of spatial presence and cognitive involvement?

- What technical or methodological factors must be addressed to improve user comfort, clarity, and engagement in IVR-based studies?

3.2 Methods

The following section discusses the methods and tools used in this research study, including limitations.

3.2.1 Software and Workflow

The virtual environment was created using an integrated software workflow designed to ensure accuracy, realism, and effective user immersion (see Figure 4). Each software was selected for its strengths. Initially, the architectural modeling was carried out using Autodesk Revit 2025, selected for its precision in creating detailed, dimensionally accurate, and spatially coherent 3D models. Revit enabled the construction of a precise architectural model, incorporating exact spatial layouts, structural details, and window configurations.

The Revit model was subsequently exported to Twinmotion 2025.1 for preliminary visualization. Twinmotion was chosen due to its flexibility and user-friendly interface, allowing efficient exploration and initial refinements of lighting conditions, spatial arrangements, and preliminary material mapping. This step facilitated rapid visualization and iterative adjustments, helping streamline the transition to advanced rendering stages.

Final rendering, material refinement, and immersive interaction were completed using Unreal Engine 5.2. Unreal Engine was selected for its photorealistic rendering capabilities, real-time ray tracing, and advanced material features. These capabilities were essential for realistically simulating the detailed visual characteristics of BIPV window configurations, such as visible light transmitance, reflectivity, and surface textures. Compared to other platforms, Unreal Engine provided smoother integration with Twinmotion, and developing VR performance, making it highly suitable for this study.

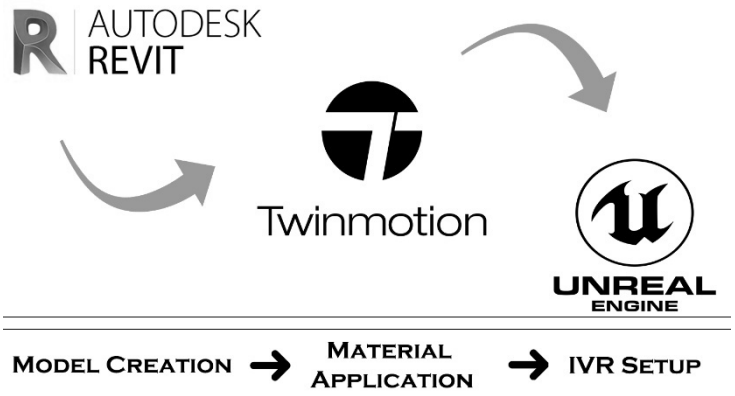


Figure 4. Software workflow for developing the IVR environment using Revit, Twinmotion, and Unreal Engine.

Participants experienced the IVR environment using a Meta Quest 2 headset, connected through Meta Quest Link software. This combination ensured seamless interaction and stable connectivity between the VR headset and the high-performance computer, crucial for maintaining real-time responsiveness, minimizing latency, and enhancing participant immersion. Reliable and smooth user interactions provided by this hardware-software integration were essential for capturing occupant feedback on visual comfort and satisfaction.

Although participants in this study remained seated and sky conditions were static, a real-time rendered IVR environment (6 degrees of freedom (DOF)) was selected over pre-rendered 360° stereoscopic images (3DOF) to enhance perceptual realism and methodological flexibility. Real-time rendering allowed participants to experience natural head movements with parallax, depth cues, and subtle perspective shifts, which are absent in 3DOF environments. These motion-based cues strengthen spatial presence and view clarity perception, even without locomotion. Additionally, the 6DOF workflow enabled rapid prototyping and adjustment of BIPV cell arrangements and optical properties during development, something far less practical with pre-rendered 360° images that require re-rendering for each configuration. This adaptability was critical for an exploratory study with multiple façade variations. On the other

hand, 360° stereoscopic images offer advantages in computational efficiency, stable lighting control, and guaranteed high visual fidelity since they are ray-traced renderings. However, they lack interactivity, are less engaging for participants, and cannot dynamically adapt to design iterations. By using 6DOF real-time rendering, this study prioritized perceptual immersion and flexibility over static photorealism, aligning with the study's aim to evaluate how participants respond to obstructed or patterned BIPV window views under controlled but realistic conditions.

In this study, IVR was used as a perceptual simulation tool to support comparative evaluations of BIPV window view experience. It was not intended for photometric analysis, and no quantitative lighting or luminance measurements were derived from the VR environment. Instead, it served to immerse participants in a realistic, controllable setting for subjective feedback. Glare metrics, including DGP and sDG, were calculated independently using validated daylight simulation tools (i.e., Radiance), but not within the VR environment. This ensured optical precision, as the IVR scenes were not designed to replicate true luminance gradients or glare effects.

3.2.2 The IVR Environment

The IVR Study Design is central to this research, offering a controlled and realistic assessment of BIPV window configurations. This section details the design elements of the virtual environment, including participant interactions, experimental setup, and data collection protocols. The selected layout and workstation distance were not chosen randomly but are grounded in established reference models and recent human-subject studies presented under literature.

The office setup for this study, with dimensions of 15 meters in width (along the façade), 8 meters in depth, and a ceiling height of 3.54 meters, was chosen to optimize the evaluation of BIPV window impacts on human window view satisfaction (see Figure 5). The 8-meter depth ensures that all areas within the office receive adequate natural light. The exclusive use of

windows on the southern facade prevents any decrease in light quality that might occur in deeper spaces, which is critical for consistent observation throughout the room.

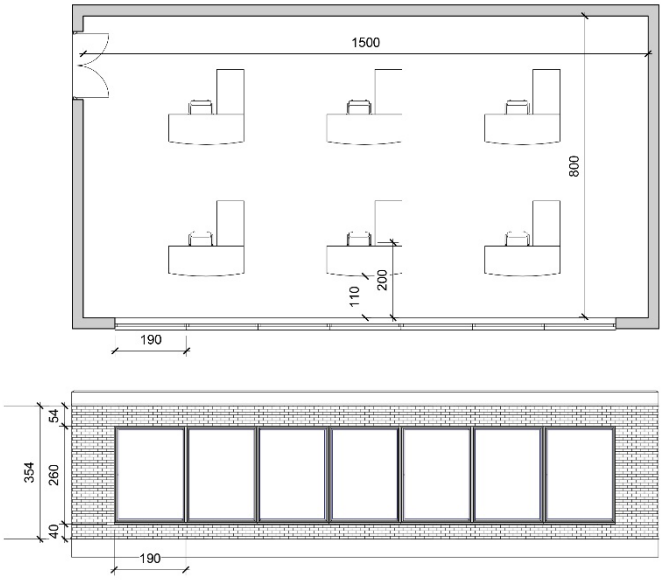


Figure 5. Layout of the open-plan office with south-facing window

The southern orientation of the BIPV windows maximizes solar exposure, crucial for maintaining high photovoltaic generation performance. Seven fixed windows, each measuring 1.9 meters in width and 2.6 meters in height with a WWR of 65.12%, are designed to offer expansive views. In the virtual environment, participants were seated behind the middle workstation in the first row, as shown in Figure 5. The chosen WWR (65.12%) similarly reflects evidence from Ko et al.'s view access index, which found that occupant satisfaction plateaus beyond ~65% WWR, and that lower WWR (<25%) severely reduces view satisfaction [82]. By fixing WWR within this empirically validated "saturation zone," the study ensures participants evaluate views under conditions consistent with high-quality office design benchmarks. They were provided with an L-shaped desk that represents a typical office desk arrangement, replicating a realistic seated viewing position at approximately 2 meters from the windows,

with an eye level of 1.20 meters from the floor. The distance of 2 m between the participant and the window corresponds to the “nearest row” workstation placement used in view access experiments. Ko et al. tested viewing distances of 2 m, 5.5 m, and 9 m, identifying these as representative zones of open-plan layouts [82]. Positioning participants at 2 m therefore places them in the optimal zone where view clarity and daylight remain strongest, while avoiding confounding issues like glare or content loss at deeper positions. This arrangement facilitated an accurate and representative assessment of the window views through the BIPV windows from a daily user's perspective. The virtual office environment was designed to replicate a typical indoor workspace, using neutral colors and realistic material finishes to minimize distraction and highlight the influence of BIPV window configurations on view quality. The walls and ceiling are modelled using neutral-toned materials, with 50% Visible Light Reflectance (RVIS) for the walls and 70% RVIS for the ceiling. The flooring is a light carpet finish with a 16% RVIS, offering low visual glare and contributing to a subdued, comfortable visual baseline. Simplifying the layout, keeping desks uniform and removing secondary variables like blinds, partitions, or multiple orientations, follows the methodological guidance of Kim et al., who emphasize reducing uncontrolled factors when using VR for view quality research [93]. This ensures that participant responses can be attributed directly to BIPV window configurations, rather than to unrelated design complexities. All desks in the scene are modeled as white-painted wooden cabinets with an 81% RVIS, ensuring high surface brightness in the field of view. The glazing used in the window assembly is a high-performance double-glazed unit, providing a Visible Light Transmittance (TVIS) of 70% and a RVIS of 10%, allowing clear views, ample daylight penetration while maintaining realistic light reflectance values. The window frame is an aluminum grey material with a 20% RVIS, visually distinct yet balanced within the neutral-toned interior. This material palette is complemented by photovoltaic cells with 24% RVIS, realistically simulating the appearance of BIPV elements when overlaid in configurations.

The silicon photovoltaic cells used in this study were modelled with a neutral gray coloration corresponding to Munsell N 5.5, a mid-value tone that approximates the appearance of many commercially available mono- and poly-c-Si BIPV windows. This choice was based on its

representativeness as a balanced visual baseline, neither highly reflective nor deeply tinted, allowing participants to focus on the effects of cell size and TVIS without the confounding influence of unusual coloration. Munsell N 5.5 is comparable to finishes found in mono- and poly- c-Si BIPV windows marketed in Europe and North America. Table 1 provides a summary of the optical material properties.

Table 1. Summary of the optical material Properties Used in the IVR Environment

Element	Material	TVIS	RVIS
Desk Surface	White Painted Wooden Cabinet	-	81%
Window Frame	Aluminum Grey	-	20%
Glazing	DGU LOW-IRON COOL-LITE XTREME 70-33 II / SWC M65	70%	10%
Floor	Light Carpet	-	16%
Ceiling	Ceiling LM83	-	70%
Wall Surface	Wall LM83	-	50%
BIPV	Munsell N 5.5	-	24%

The final environment (see Figure 6) maintains a consistent aesthetic and lighting balance, helping participants focus on the clarity and quality of the view through the window rather than being influenced by strong interior contrasts or design. These material and lighting choices ensure that the space realistically represents a typical office setting while being technically suitable for visual performance studies. By adopting these specific dimensions and arrangements, the office layout is structured for an in-depth investigation into how variations in solar cell size and TVIS of BIPV windows affect the quality of views perceived by occupants.



Figure 6. The IVR Environment simulating a 15 × 8 m office used to assess occupant perception of BIPV window views.

3.2.3 Study Ethics

This study was reviewed and received ethics clearance from the University of Waterloo's Office of Research Ethics under protocol number #46608, titled "Evaluating Window View Quality of Building-Integrated Photovoltaic Using Virtual Reality." The study was approved on July 30, 2024, and will remain valid until July 31, 2026.

Participant Rights and Informed Consent: All participants were fully informed about the study's purpose, procedures, risks, and confidentiality policies. They were provided with an Information Letter and asked to sign a written consent form prior to participation. Participation was entirely voluntary, and individuals could withdraw at any point without penalty. If a participant chose to withdraw, all associated data was immediately discarded and excluded from the analysis.

Inclusion and Exclusion Criteria: Recruitment targeted the University of Waterloo's Students, ensuring they had normal or corrected-to-normal vision, with exclusion of individuals with

significant visual impairments or a history of motion sickness, severe anxiety, claustrophobia, epilepsy, cognitive impairments, or other conditions potentially affecting comfort or data reliability. Participants were explicitly requested to avoid alcohol and smoking on the night preceding their scheduled test session to ensure optimal cognitive and visual performance. For safety and comfort, pregnant women were advised not to participate, prioritizing their comfort and safety. Individuals diagnosed with Attention-Deficit/Hyperactivity Disorder (ADHD) were also excluded to minimize potential distractions and ensure consistent evaluation conditions. Participants were recruited from ages 18 to 40 due to their typically stable visual acuity. All eligibility criteria and exclusions relied solely on participant self-reporting, with no medical or diagnostic tests performed by the researcher.

Risk Management and Safety Measures: Risks associated with VR use such as motion sickness, eye strain, and disorientation were explicitly disclosed in advance. To mitigate these risks:

- Participants remained seated during IVR sessions,
- Headsets were carefully adjusted for comfort,
- Breaks were offered to reduce fatigue,
- Participants could stop the experiment at any time if discomfort occurred.

Additionally, technical support was available throughout the sessions, and basic first aid resources were accessible onsite.

Privacy, Confidentiality, and Data Protection: Each participant was assigned a unique study ID number to anonymize their data. All identifying information (e.g., names, contact details) was stored separately in a locked cabinet in a secure research facility. Only the research team had access. Anonymized study data, including questionnaires and sensor-based environmental readings, were securely stored in both hard copy and electronic formats. All data will be retained for five years, after which physical documents will be confidentially shredded.

This research adheres strictly to the Tri-Council Policy Statement (TCPS 2) guidelines for the ethical conduct of research involving human participants.

3.2.4 Recruitment of participants

Participants were recruited in accordance with the approved ethics protocol (ORE#46608) using a combination of convenience and purposive sampling methods. Recruitment targeted adults above 18, reflecting a population commonly found in office environments, which aligns with the study's context of window view evaluation in workplace settings.

Recruitment Procedure: Participants were recruited through:

- Posters and flyers displayed in campus buildings,
- Email invitations distributed through department mailing lists,
- Word-of-mouth referrals from students and staff.

All recruitment materials were pre-approved by the University of Waterloo's Office of Research Ethics and included essential information such as eligibility criteria, study purpose, contact details, and the right to voluntary participation and withdrawal.

Interested individuals contacted the research team via email and were sent the Information Letter and Consent Form. Before participating, everyone was screened for eligibility and provided informed written consent. No incentives were offered for participation, and the involvement was entirely voluntary.

3.2.5 Hypotheses and questionnaire design

The hypotheses and questionnaire were designed to assess the effectiveness of the virtual simulation in providing a perceptually realistic and immersive experience, without requiring direct comparison to a corresponding real-world space.

The following hypotheses are proposed to guide the evaluation of participant experience within the IVR environment.

- H_{1-1}: Participants will perceive the IVR environment as visually realistic and experientially credible, based on their general familiarity with typical office settings.
- H_{1-2}: The IVR environment will generate a strong sense of spatial presence, leading participants to feel physically situated within the virtual office.
- H_{1-3}: Participants will experience high levels of cognitive and emotional involvement during their interaction with the virtual scene.

These hypotheses aim to confirm that the IVR setup provides sufficient perceptual fidelity and user engagement to support occupant-centered evaluation.

To assess these hypotheses, a questionnaire adapted from Abd-Alhamid et al. [108] was used. While Abd-Alhamid's original study involved a direct comparison between virtual and real environments, that approach was outside the scope of this feasibility study. Therefore, this study uses the same questions to assess participants' perceptions of the virtual scene, drawing on their general experiences in typical office spaces.

The questionnaire includes three core dimensions:

Realness Question: "*Your experience in the virtual environment was consistent with your real-world experiences* [108]."

Purpose: This question directly assesses the similarity between participants' experience within the IVR simulation and their real-world perceptions. As Abd-Alhamid et al. [108] explain, realness evaluates how effectively visual and sensory elements replicate an authentic environment. By measuring realness, the IVR simulation's credibility as a realistic substitute for a physical test environment is assessed. Achieving high realism ensures participants respond similarly in virtual conditions as they would in real conditions, making the study's findings reliable and transferable to real-world settings.

Spatial Presence Question: "*During the study, I felt 'being there' in the virtual environment* [108]".

Purpose: Spatial presence captures the participant's subjective sense of physically occupying the virtual environment. According to Abd-Alhamid et al. [108], spatial presence is crucial because it confirms the IVR environment's ability to recreate realistic spatial awareness and depth perception, essential for participants to interact naturally with the virtual content. Ensuring high spatial presence indicates the IVR environment effectively reproduces the real-world spatial relationships and perceptions critical for accurately evaluating spatial design elements like window view quality.

Involvement Question: "*During the study, the virtual environment became a reality for me* [108]".

Purpose: Involvement measures the extent of participants' cognitive and emotional engagement with the virtual scene, essentially reflecting how believable and absorbing the simulation felt. Abd-Alhamid et al. [108] highlight involvement as vital to confirm that participants are genuinely interacting with the virtual environment rather than passively observing it. High involvement ensures participants provide authentic and thoughtful responses, thereby enhancing the reliability of collected data.

These three presence dimensions, Realness, Spatial Presence, and Involvement, collectively cover all critical aspects required to evaluate an IVR environment. Realness confirms visual and experiential authenticity; Spatial Presence ensures participants perceive correct spatial relationships; Involvement verifies participants' cognitive and emotional engagement. Together, these three dimensions ensure the IVR environment's methodological soundness, realism, and immersive quality used in this research.

Table 2 presents the three parameters adapted from the Presence Questionnaire [108], which were used to evaluate participants' subjective experience in the immersive virtual environment. Each parameter was rated on a 7-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree), with 0 representing a neutral response. This scale allows for capturing the intensity of participant perceptions across the dimensions of realness, spatial presence, and involvement.

Table 2. The Presence Questionnaire Used to Assess Immersive Experience in the Virtual Environment

Parameters	Statement	Response*
Realness	Your experience in the virtual environment was consistent with your real-world experiences [108]	-3 (strongly disagree) to +3 (strongly agree)
Spatial Presence	During the study, I felt "being there" in the virtual environment[108]	-3 (strongly disagree) to +3 (strongly agree)
Involvement	During the study, the virtual environment became a reality for me [108]	-3 (strongly disagree) to +3 (strongly agree)

* Each parameter was rated on a 7-point Likert scale ranging from -3 (strongly disagree) to +3 (strongly agree), with 0 indicating a neutral response. This scale was used to quantify participants' subjective perception of presence in the IVR.

3.2.6 Experimental design and procedure

Ethical and ergonomic considerations were integrated throughout the procedure to ensure participant comfort, safety, and data reliability.

Test Environment: All experimental sessions were conducted in Room E2-3321, located in the Department of Civil and Environmental Engineering at the University of Waterloo. The room is a private, medium-sized meeting space, equipped with a rectangular conference table, seven task chairs, a display screen, and standard ceiling lighting fixtures. The space features four large windows with manual roller shades that can be adjusted to control natural light (see Figure 7).



Figure 7. Physical Setup of Experimental Room (E2-3321) Showing Actual Window Geometry and Indoor Lighting Used for VR Calibration

To ensure comfort and environmental stability during each session, temperature and relative humidity were recorded using a SPER Environmental Quality SD Card Datalogger (see Figure 8). Readings were monitored before each session to ensure consistency across participants.



Figure 8. SPER Environmental Quality Datalogger used to measure temperature and humidity

Equipment Setup: The experiment utilized the Meta Quest 2 headset for the IVR experience. The headset was connected to a high-performance laptop to ensure smooth rendering, with cables and seating arranged to minimize motion constraints or tripping hazards. Participants

remained seated at the conference table during the session to reduce the risk of falls or discomfort during VR use. All VR content was preloaded onto the headset, providing photorealistic representations of a clear window scenario in a virtual office.

Participant Procedure: Each participant booked a private, 30-minute session in advance. Upon arrival, they were welcomed by the researcher and introduced to the study.

- Participants reviewed and signed a consent form. They also completed a short demographic questionnaire, which collected information about age, gender at birth, contact details, and visual health (e.g., glasses or contact lenses).
- A 5-minute introduction was provided explaining the study goals, equipment, tasks, and timeline. Participants were encouraged to ask questions and voice concerns.
- Participants were seated, fitted with the Meta Quest 2 headset, and given 3 minutes to adjust to the VR environment. This ensured both visual clarity and user comfort before data collection began.
- Once comfortable, participants were presented with a clear window configuration in the IVR environment. They were instructed to explore the scene passively for about 1 minute, after which the researcher verbally asked each Presence Questionnaire item (Section 2.2.5) and entered the participant's responses directly into a pre-prepared Excel spreadsheet.
- Participants remained seated in the room for five minutes after the session to monitor for any discomfort, fatigue, or VR sickness. No participant reported any adverse effects during this period.
- The viewpoint within the VR environment was fixed at a seated eye level of 1.20 meters. This position was selected to represent a typical working posture facing the façade, where view clarity and glare perception are most relevant. Although participants were free to look around, nearly all naturally assessed the view while seated and facing the window directly [93].

- After leaving the session, each participant received a follow-up thank-you and feedback email, with an option to request a summary of findings at the end of the research.
- No audio or video recording was used to ensure privacy.
- Meta Quest 2 was sanitized between sessions to meet hygiene protocols.
- To minimize visual distortion and maintain consistency in perceived window clarity, all VR scenes were rendered under diffuse sky conditions without direct sunlight. This approach was chosen to avoid glare artifacts and ensure that clarity evaluations reflected view openness, not excessive luminance contrast.

3.2.7 Initial Pilot Test and Technical Challenges and Solutions

A pilot test involving 10 participants was conducted to evaluate the clear window configuration alongside three specific BIPV window configurations (Configurations 3, 6, and 9) within the IVR environment. The purpose of the pilot was to identify and resolve any technical, visual, or participant comfort-related issues before proceeding to the full evaluation study.

During this initial phase, several challenges emerged. These were identified through a combination of direct observation, participant feedback, and informal interviews conducted immediately after each session. Table 3 discusses all issues with targeted adjustments to improve the overall realism, usability, and participant well-being within the IVR setting.

Table 3. Technical and User-Related Challenges Encountered During IVR Development and Their Implemented Solutions

Technical/User-Related Challenges	Implemented Solution
Latency and Connectivity Issues	Replaced wireless Air Link connection with wired Meta Quest Link cable to significantly reduce latency and improve VR stability.
Fatigue Management	Limited evaluation sessions to a maximum of four configurations, reducing participant fatigue and cognitive overload
Achieving Photorealistic Visual Quality	Adopted Unreal Engine 5.2, utilizing advanced rendering techniques and real-time ray tracing.
Abrupt Transition Between Configurations	Improved transitions between configurations, implementing smoother, gradual visual shifts to minimize participant discomfort.
Consistent Lighting Conditions	Carefully recalibrated lighting settings in Twinmotion and Unreal Engine, ensuring consistent and realistic lighting conditions across all tested scenarios.
Participant Comfort, Navigation, and Comprehension	Provided structured introductory sessions clearly defining study objectives and evaluation criteria and ensured sufficient time for participants to become comfortable with IVR controls.

Latency and Connectivity Issues: Participants reported noticeable delays and jerky visuals, particularly evident when making rapid head movements. This latency issue was traced to the wireless "Air Link" connection used by the Meta Quest headset. The latency negatively affected participants' immersion, causing discomfort and significantly reducing the perceived realism of the virtual environment. To resolve it, the wireless connection was replaced with a wired Meta Quest Link cable. This wired setup greatly reduced latency, significantly enhanced VR stability, and notably improved participants' comfort and overall sense of immersion.

Participant Fatigue and Cognitive Overload: Participants experienced fatigue and reduced concentration after evaluating multiple window configurations consecutively. Specifically, noticeable cognitive overload occurred after participants viewed more than four

configurations, resulting in decreased attention and inconsistent evaluation responses. Observations of participants' body language, informal discussions, and verbal feedback were instrumental in identifying this issue. To address this, the evaluation protocol was adjusted, limiting each participant's session to a maximum of four configurations. This approach substantially reduced participant fatigue, increased sustained engagement, and improved the reliability and clarity of the feedback collected.

Insufficient Visual Realism: Participants consistently indicated that certain visual aspects appeared unrealistic, negatively impacting their experience. Issues raised included inadequate texture resolution, inaccurate material simulations, and unrealistic lighting effects. Post-session interviews and participant discussions clearly highlighted the need for improved visual realism. To address this, the rendering workflow was transitioned to Unreal Engine 5.2, leveraging its advanced rendering techniques, real-time ray tracing capabilities, and enhanced material simulations. This change significantly improved visual realism, directly enhancing participant satisfaction with the virtual environment.

Abrupt Transition Sequences: Participants frequently noted that the transitions between different window configurations were disruptive, causing brief disorientation and discomfort. Observations during testing and direct participant feedback consistently identified this issue. To enhance participant comfort, smoother and more gradual transitions between configurations were implemented in Unreal Engine. This refinement significantly reduced discomfort, improved continuity, and provided participants with a more comfortable and natural testing experience.

Inconsistent Lighting Conditions: In initial participant feedback revealed noticeable variations in lighting conditions between different configurations, leading to inconsistent evaluations of window views. Observations during sessions further confirmed discrepancies in lighting uniformity. To address this, recalibration of lighting settings was performed within both Twinmotion and Unreal Engine, ensuring consistent and realistic lighting across all test

scenarios. This adjustment improved the consistency and reliability of participant assessments of window views.

Difficulty with Navigation, Interaction, and Study Comprehension: Initially, participants experienced challenges navigating the IVR environment and using the VR controllers effectively. Direct observations during the early sessions indicated confusion and hesitation, impacting participants' ability to fully engage with the IVR content. Additionally, informal feedback suggested participants were not entirely sure about the purpose of the study, the specific aspect of the window views they were asked to evaluate, or the criteria they should use for rating these views. To address these challenges, structured introductory sessions were added at the beginning of each participant's testing session. These sessions provided clear, neutral instructions about the study's objectives, explaining precisely what "window view quality" referred to, and outlined the evaluation criteria without influencing personal judgments. Participants also received sufficient time to practice headset adjustments and controller functionalities. This approach greatly enhanced participants' understanding of the task, improved their comfort and confidence within the IVR environment, and led to more accurate, consistent, and relevant responses.

These refinements, identified through observation and participant feedback, significantly enhanced the robustness of the IVR methodology, ensuring accurate and reliable outcomes for subsequent phases of the study.

The pilot test involved 10 participants and was used exclusively to validate the experimental setup, equipment calibration, and data collection workflow. The results of the pilot were not included in the final statistical analysis. Following the resolution of these challenges, the main evaluation study proceeded with 20 participants, the detailed results of which are presented in the subsequent sections.

3.3 Statistical Analysis and Results

To evaluate the immersive quality of the refined IVR environment, statistical analyses were conducted using R software (version 4.5). R was selected due to its statistical capabilities, flexibility, and wide range of available packages suitable for non-parametric analyses, making it particularly effective for analyzing ordinal questionnaire data like the Presence Questionnaire used in this study.

The analysis aimed to determine whether participant ratings for the Presence Questionnaire dimensions, Realness, Spatial Presence, and Involvement, were significantly greater than the neutral midpoint of 0 on a 7-point Likert scale ranging from −3 (strongly disagree) to +3 (strongly agree).

3.3.1 Descriptive Statistics

Descriptive statistics were used to summarize and clearly communicate the central tendencies (mean and median values) of participant responses, providing an initial understanding of overall trends and distributions within the data.

Figure 9 provides the boxplots for the descriptive statistics for each dimension. Participants generally reported positive ratings across all dimensions, with the highest ratings observed for spatial presence. The mean scores indicate that Spatial Presence had the highest average rating (1.35), followed by Involvement (1.15), and Realness (0.95). Median values show that both Realness and Involvement had a central tendency of 1.0, while Spatial Presence had a higher median of 1.5, suggesting participants generally experienced a stronger sense of spatial presence compared to the other dimensions.

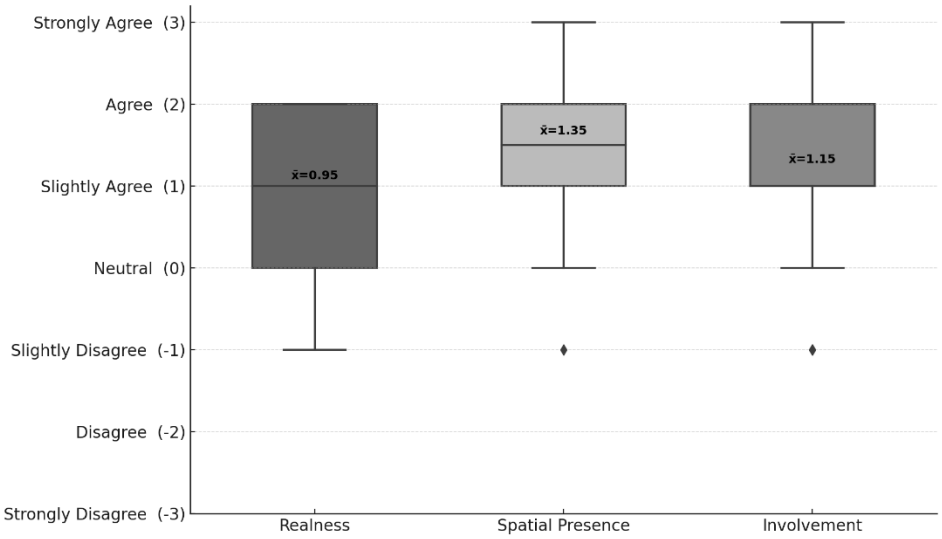


Figure 9. Distribution charts summarizing participant responses for Realness, Spatial Presence, and Involvement. Spatial Presence received highest and most consistent ratings, while Realness showed the greatest variability.

These results suggest that the IVR environment developed in this study was effective in evoking a meaningful sense of spatial presence. Although the average ratings for realness and involvement fell between “slightly agree” and “agree” and individual variability was observed, such outcomes are consistent with other validation studies, which note that achieving perfect realism in VR is rarely possible due to hardware and rendering limitations. Importantly, the consistently positive ratings for spatial presence, combined with generally favorable responses across all three dimensions, indicate that the environment was immersive enough to support occupant evaluation of BIPV window views. In this context, “sufficiency” does not imply absolute replication of real life, but rather providing a perceptually credible and controlled testbed that enables comparative judgments between different façade conditions.

Realness: Participants provided moderately positive ratings for realness (mean = 0.95, SD = 1.02), with responses largely clustered around +1 (slightly agree) and +2 (agree). While this indicates general satisfaction with IVR's visual accuracy and fidelity to real-world

experiences, the distribution revealed that four participants (20%) reported neutral ratings, and two participants (10%) gave slightly negative ratings. This suggests that the realism in the IVR setup was acceptable to most, but some discrepancies, potentially related to graphical limitations or minor technical issues, impacted a subset of participants.

Spatial Presence: Spatial presence received the highest mean rating among the three dimensions (mean = 1.35, SD = 0.93). The data indicated robust and consistent perceptions of spatial realism, as evidenced by most participants (80%) providing ratings of +2 (agree) or +3 (strongly agree). Only three participants (15%) rated their sense of spatial presence neutrally, and no strongly negative ratings were observed.

Involvement: Involvement received a moderate-to-high positive evaluation (mean = 1.15, SD = 1.02). Most participants (75%) provided ratings between +1 (slightly agree) and +2 (agree), signifying substantial emotional and cognitive engagement with the IVR environment. However, a notable variability was present, with three participants (15%) assigning neutral ratings and two participants (10%) slightly negative ratings, suggesting differing levels of cognitive and emotional engagement.

3.3.2 Inferential Statistics

To carefully assess whether the observed positive ratings significantly differed from the neutral midpoint (0), a one-sample Wilcoxon signed-rank test was deployed. This non-parametric test is particularly suitable for data that do not meet the assumptions of normality, commonly the case with ordinal Likert-scale responses.

Table 4 summarizes the statistical test results across the three dimensions: Realness, Spatial Presence, and Involvement, revealing that all received significantly positive ratings relative to the neutral midpoint. As summarized in Table 4, all three dimensions demonstrated statistically significant differences from the neutral midpoint (0), confirming that the IVR environment was perceived as realistic, immersive, and engaging by participants.

Table 4. Results of the One-Sample Wilcoxon Signed-Rank Test for Presence Questionnaire Dimensions

Dimension	P-value	Interpretation
Realness	0.003	Significantly greater than neutral
Spatial Presence	0.000150	Strong evidence of perceived spatial immersion
Involvement	0.000489	Participants were cognitively and emotionally engaged

Realness: Wilcoxon Signed-Rank Test confirmed the significance of these results ($p = 0.003$), indicating that overall perceptions of realness were significantly better than a neutral standpoint.

Spatial Presence: Statistically, this dimension showed very strong evidence that participants felt immersed and physically situated within the IVR environment ($p < 0.001$). This strongly positive result confirms the IVR environment's effectiveness in realistically simulating spatial depth and physical presence.

Involvement: The Wilcoxon Signed-Rank Test result ($p < 0.001$) demonstrated that involvement ratings significantly exceeded the neutral baseline. This indicates the IVR environment effectively fostered emotional and cognitive engagement, although variability highlights potential areas for enhancing participant immersion and interaction strategies in future implementations.

3.3.3 Summary of Results

The analysis of the IVR environment across Realness, Spatial Presence, and Involvement confirms that participants generally held positive perceptions. Spatial Presence emerged as particularly strong, affirming IVR's suitability for spatial evaluations. Although Realness and Involvement were positively perceived, the moderate variability underscores opportunities for targeted improvements to enhance IVR fidelity and participant engagement further.

3.4 Discussion

The IVR environment developed in this study received overall positive participant ratings across three perceptual dimensions: spatial presence, realness, and involvement. Among these, spatial presence was rated the highest, suggesting that users experienced a convincing sense of "being there" in the virtual space. This aligns with prior validation studies such as Chamilothori et al. [88] and Abd-Alhamid et al. [108], which found immersive VR environments capable of conveying spatial characteristics with high perceptual accuracy. These results suggest that the IVR setup is suitable platform for supporting occupant-centered design evaluations in controlled virtual contexts.

While realness was also rated positively, it showed greater individual variability. This likely stems from a combination of technical factors (e.g., rendering fidelity, resolution, lighting contrast) and user-related factors such as prior VR experience. Participants familiar with high-end VR applications or gaming environments may have noticed visual limitations more readily than those with less exposure. Although this study did not measure prior experience directly, the variation in ratings suggests that user expectations and familiarity play a role. To address this, future IVR applications should include clear onboarding, expectation setting, and continued refinement of visual realism.

Involvement, reflecting emotional and cognitive engagement, received moderate and variable ratings as well. This finding is consistent with prior research, including Ingabo et al. [111], which suggests that users may remain cognitively engaged while still being aware of the artificial nature of virtual experiences, particularly during shorter exposure durations. Increasing user adaptation time or task immersion may help enhance involvement scores in future studies. Additionally, combining self-reported measures with biometric or behavioral indicators, such as eye tracking, heart rate, or movement, could provide more accurate insights into participant engagement.

Taken together, these results indicate that the IVR platform developed in this study achieves a sufficient level of perceptual credibility to proceed with user-centered evaluations of

architectural elements such as BIPV window configurations. Although environmental factors (e.g., daylight variation, material light response) were not assessed in this phase, the platform's strength in delivering a spatially immersive experience makes it suitable for early-stage perceptual testing. Future development should prioritize enhancements to visual fidelity and interaction quality to further reduce perceptual variability and improve user engagement consistency across diverse participant profiles.

3.5 Limitations and Future Recommendations

While this study demonstrates IVR's feasibility as a methodological tool for evaluating occupant satisfaction with BIPV window views, several limitations related to the validity and feasibility assessment must be acknowledged:

Indirect Realism Assessment: Participants assessed the realism and spatial presence of the IVR environment based on their general real-world experiences rather than directly comparing it to an identical real-world environment. The lack of direct real-world comparisons limits certainty about the extent to which IVR evaluations reflect true occupant perceptions in physical environments.

Participant Familiarity with BIPV: Most participants lacked previous direct experience with real-world BIPV window installations. As a result, their feedback on realism and satisfaction with BIPV windows may be based on incomplete or generalized expectations rather than informed by specific real-world experiences.

Limitations in Evaluating View Clarity in IVR: Emerging validation studies (e.g., Kim et al. [93]) indicate that IVR may not be fully reliable for assessing view clarity due to limitations in accurately simulating luminance contrast, depth, and glare-related phenomena. In this study, clarity evaluations were conducted under diffuse daylight conditions, intentionally excluding direct sunlight to avoid distortions in VR rendering. IVR was used as a perceptual proxy to assess relative clarity preference, while glare and luminance were evaluated separately using

Radiance-based simulations. Nevertheless, this limitation should be considered when interpreting the findings related to clarity.

Technical and Visual Fidelity Variations: Although significant improvements were made through pilot testing, subtle variations in view quality, lighting consistency, and rendering fidelity within IVR simulations may still affect participants' perceptions of realism and involvement. Ensuring consistently high visual fidelity remains challenging, influencing the precision of perceptual evaluations.

Short-term Interaction and Adaptation: Participants interacted with the IVR environment for relatively brief sessions, limiting insights into how perceptions of realism, involvement, and spatial presence might evolve with longer exposure or repeated interactions.

3.6 Future research recommendations

Future studies should incorporate parallel assessments comparing IVR scenarios directly to identical physical environments to better evaluate IVR as an accurate methodological tool. Prior to IVR assessments, future studies could introduce structured familiarization sessions with real-world BIPV windows to ensure more informed and accurate participant evaluations. It also important to conduct longitudinal studies exploring how prolonged or repeated exposure to IVR environments affects participant perceptions of realism, spatial presence, and involvement, thereby providing more robust evaluation of IVR methodology. Finally, future studies should further refine visual rendering techniques and lighting simulations to achieve more consistent realism, thus enhancing the methodological reliability of IVR assessments for building performance and design evaluations.

Chapter 4

Human Subject Evaluation of BIPV Window View Quality

4.1 Introduction

This chapter investigates occupant satisfaction with nine different BIPV window configurations using a human-centric evaluation approach. A previous study, detailed in Chapter 3, evaluated the IVR setup to determine whether it replicates real-world environments. The results showed high perceptual realism, spatial presence, and user involvement, establishing IVR as a perceptually credible platform for evaluating occupant satisfaction.

Building on this methodology, this study addresses a critical gap in the literature by systematically examining how key BIPV design parameters affect the occupant perception of view clarity, privacy, and overall satisfaction.

The study addresses the following research questions:

- How do occupant perceptions of view clarity and view privacy influence their overall satisfaction with different BIPV window configurations?
- Does gender influence the relationship between occupants' perceptions (view clarity and view privacy) and their overall satisfaction with the window view?

This chapter proceeds by outlining the research hypotheses, detailing the research methodology, presenting the results of the human-subject evaluation, and concluding with a discussion of the findings in relation to the initial hypotheses.

4.2 Methods

4.2.1 Experimental Design

To systematically investigate the key design parameters, two-phase experimental design was used. The first phase isolated the effect of one variable (solar cell size), and the second, based on those findings, investigated the effect of a second variable (TVIS).

The study was structured as follows:

Pilot Test: A preliminary pilot test involving 10 participants was first conducted to refine the evaluation procedures, clarify the survey questions, and ensure participant understanding and comfort. Details of the pilot test protocol, observed challenges, and implemented solutions are provided in Appendix D.

Phase 1: Solar Cell Size Evaluation: The goal of this phase was to determine how different solar cell sizes affect participant perceptions of view clarity, view privacy, and overall satisfaction while holding the level of TVIS constant. This phase involved a group of 20 participants, with an approximately equal gender distribution.

Phase 2: TVIS Evaluation: The results from Phase 1 were used to select the occupant-preferred solar cell size. This cell size was then used in Phase 2 to evaluate how varying levels of TVIS impact occupant window view satisfaction. This phase involved a separate group of 40 participants, also approximately equal in gender distribution.

Participant recruitment adhered to the approved methodology outlined previously (see Section 3.2.4). Participation was entirely voluntary, ensuring ethical compliance and unbiased responses.

The total number of participants in this study was not based on a formal a priori power analysis. In human subject research on indoor environmental quality (IEQ) and window view perception, logistical and recruitment challenges often constrain sample sizes, since experiments are time-intensive and require controlled laboratory conditions. Consequently, many prior IEQ and view quality studies (see Appendix B) report comparable sample sizes, typically ranging between 20–60 participants for VR or laboratory-based evaluations. The sample size adopted here is therefore consistent with established practice in this field, providing sufficient diversity for meaningful analysis while remaining feasible within resource and ethical constraints.

4.2.2 Hypotheses and Questionnaire Design

The study was guided by four hypotheses to evaluate the impacts of BIPV window configurations on occupant perceptions of window view quality:

Hypotheses:

- H_{2-1}: Variations in solar cell size significantly affect occupant perceptions of view clarity and view privacy.
- H_{2-2}: Different levels of TVIS significantly affect occupant perceptions of view clarity and view privacy.
- H_{2-3}: Occupants' perceptions of view clarity and view privacy significantly predict their overall satisfaction with window views.
- H_{2-4}: Gender significantly moderates occupants' perceptions and satisfaction regarding view clarity, view privacy, and overall window view satisfaction.

4.2.3 BIPV Configurations and Key Variables

Nine BIPV window configurations were designed and simulated in the IVR environment to test the study's hypotheses. The specific layouts are detailed in Table 5 and visualized in Figure 10. The configurations were created by systematically varying two key variables over two phases, as illustrated in the flowchart in Figure 11:

Phase 1. Solar Cell Size: Three sizes were tested: Full size (21 cm x 21 cm), Half size (21 cm x 10.5 cm), and One-third size (21 cm x 7 cm). Larger solar cells visually reduce the open view areas but provide clear gaps between cells. This variable was the focus of Phase 1.

Phase 2. TVIS: Three TVIS levels were tested: 0.26, 0.37, and 0.48. Higher TVIS values offer greater TVIS, potentially improving clarity but affecting privacy. This variable was the focus of Phase 2.

All simulations used mono- and poly- crystalline silicon (c-Si) cells, as this technology's efficiency, durability, and design flexibility are well-suited for BIPV applications. A clear

reference window (TVIS = 0.702) was also included for comparison. The focus is placed specifically on mono- and poly-crystalline silicon (c-Si) BIPV windows, which represent the most commercially mature and widely deployed BIPV cell type. These mono- and poly-Si modules differ fundamentally from semi-transparent or thin-film BIPV windows: while the latter allow partial visual transmission and pattern-based visibility, mono- and poly-crystalline Si cells fully block transmitted light through the active area of the module. As a result, they create a distinctive appearance, characterized by discrete dark rectangular cells arranged within the insulating glass unit (IGU), which segment and partially obstruct the outward view. This distinguishes them visually and functionally from other BIPV window products, where the perception of the outdoors is filtered but not partially blocked. By clarifying this distinction, the experimental scope of this research is narrowed to a specific class of BIPV windows that prioritizes efficiency and commercial availability, while posing the most pronounced challenges to view clarity and occupant satisfaction.

The tested cell sizes (full, half, and one-third of a standard c-Si cell) were derived from practical manufacturing dimensions used in BIPV modules. These discrete increments reflect common cutting and patterning practices. Similarly, the three TVIS levels tested in this study (0.26, 0.37, and 0.48) were not specific to a single product but represent a range observed in available commercial mono- and poly-crystalline Si BIPV windows with varying packing factors. By selecting representative yet controlled values, the study ensured generalizability while maintaining methodological clarity.

Table 5. Ten BIPV window cell arrangement, double glazed IGU

Configuration Number		Number of Horizontal Cells	Number of Vertical Cells	Horizontal Spacing between the cells (mm)	Vertical Spacing (mm)	Total TVIS**	Estimated Electrical Efficiency *
0	Clear Window (reference)	0	0	0	0	0.702	0%
			Full Cell Size (21 cm*21 cm)				
1	Full-size cell, TVIS=0.26	8	8	2	106	0.256	14 %
2	Full-size cell, TVIS=0.37	8	6	2	233	0.368	11 %
3	Full-size cell, TVIS=0.48	8	4	2	528	0.479	7%
			Half Cell Size (21 cm*10.5 cm)				
4	Half-size cell, TVIS=0.26	8	16	2	50	0.256	14 %
5	Half-size cell, TVIS=0.37	8	12	2	106	0.368	11 %
6	Half-size cell, TVIS=0.48	8	8	2	226	0.479	7%
			1/3 Cell Size (21 cm*7 cm)				
7	1/3-size cell, TVIS=0.26	8	24	2	32	0.256	14 %
8	1/3-size cell, TVIS=0.37	8	18	2	68	0.368	11 %
9	1/3-size cell, TVIS=0.48	8	12	2	144	0.479	7%

* Calculated as follows: Electrical Efficiency = 20% * Packing Factor

** Total TVIS = Clear window's TVIS * (1-Packing Factor)

*** Packing Factor = Number of Horizontal Cells * Number of Vertical Cells * (Full Cell Surface area/Window Surface area)

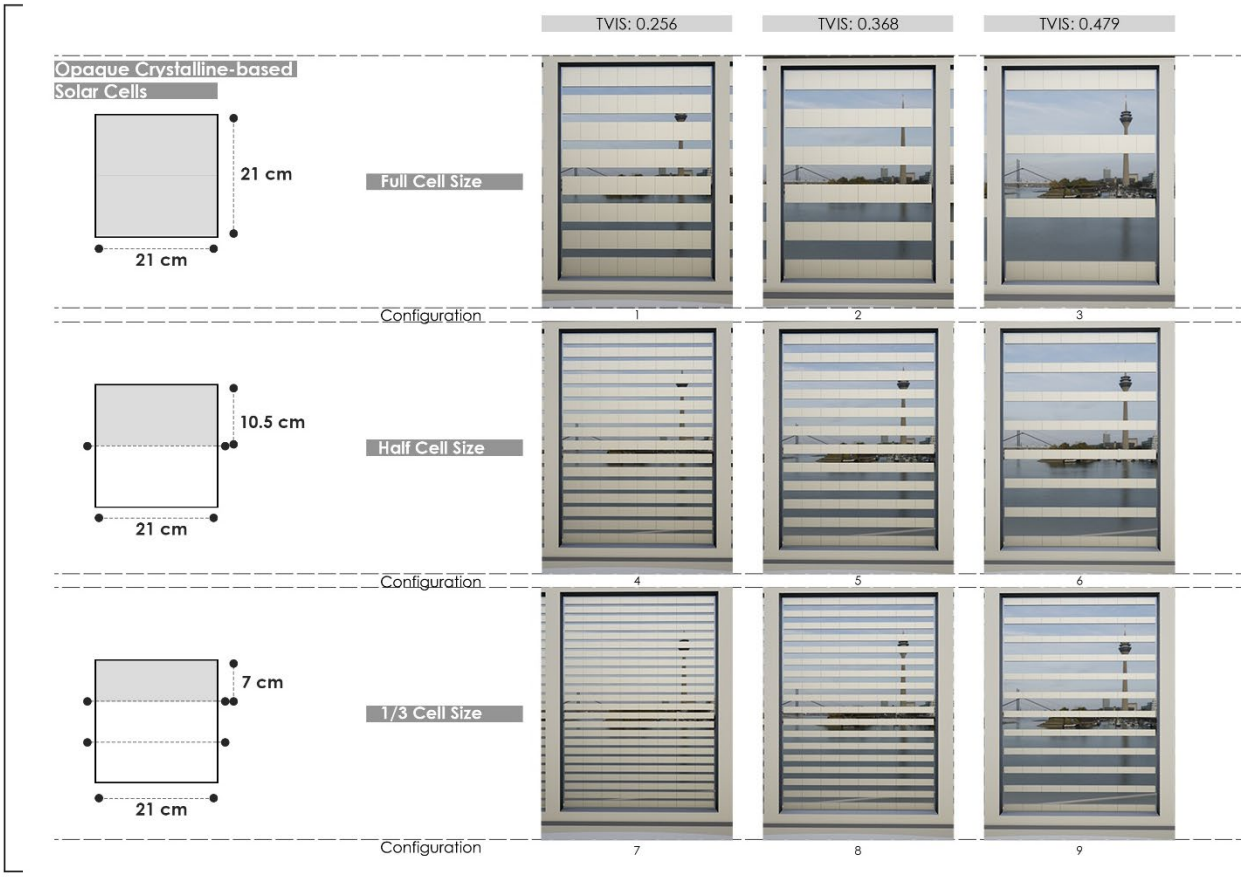


Figure 10. Design Matrix of BIPV Window Configurations for the Two-Phase Experimental Selection Study

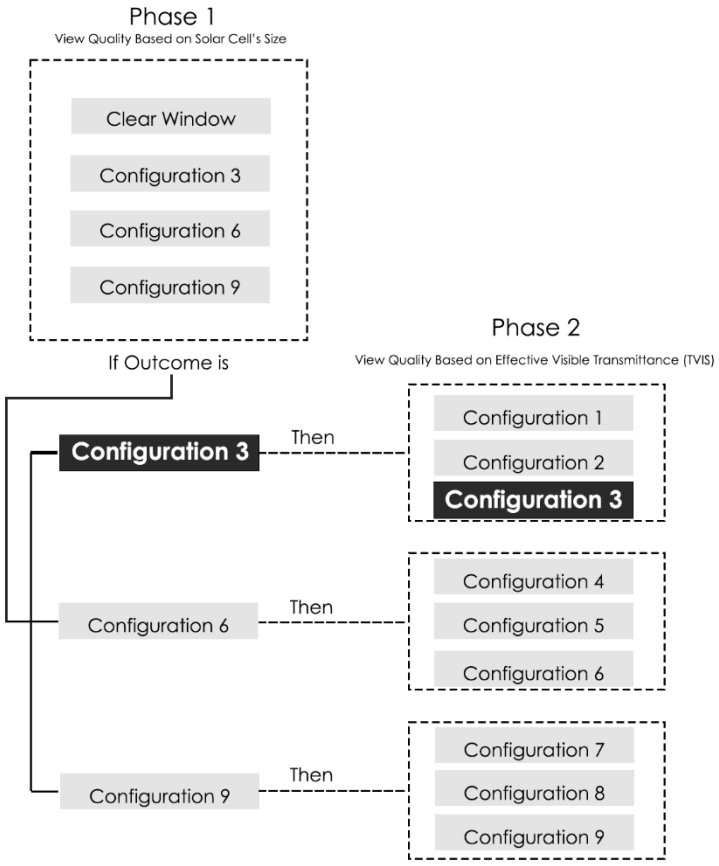


Figure 11. Flow chart for the two-phase BIPV window configuration selection process based on survey outcomes

4.2.4 Survey Instrument and Evaluation Metrics

A questionnaire was developed to measure occupant satisfaction across three key dimensions: view clarity, view privacy, and overall satisfaction. The survey questions adapted from validated scales used in previous window view quality studies to ensure reliability and comparability [93].

The questionnaire focused on these three key dependent variables; each rated on a 7-point scale from –3 (Very Dissatisfied) to +3 (Very Satisfied) (see Table 6).

Table 6. Survey Questions for Evaluating User Perception of BIPV Window Views Across Key Visual Metrics (Clarity, Privacy, Overall Satisfaction)

Evaluation Metric	Survey Question	Response Scale
View Clarity	How satisfied/dissatisfied are you with the clarity of your window view? [93]	7-point scale from –3 ("Very Dissatisfied" to +3 ("Very Satisfied").
View Privacy	How satisfied/dissatisfied are you with the level of view privacy through the window? [93]	7-point scale from –3 ("Very Dissatisfied" to +3 ("Very Satisfied").
Overall Satisfaction	All things considered, how satisfied/dissatisfied are you with the overall window view? [93]	7-point scale from –3 ("Very Dissatisfied" to +3 ("Very Satisfied").

View Clarity (Figure 12): This question assesses occupant satisfaction with the sharpness and distinctness of visual elements visible through the BIPV windows.

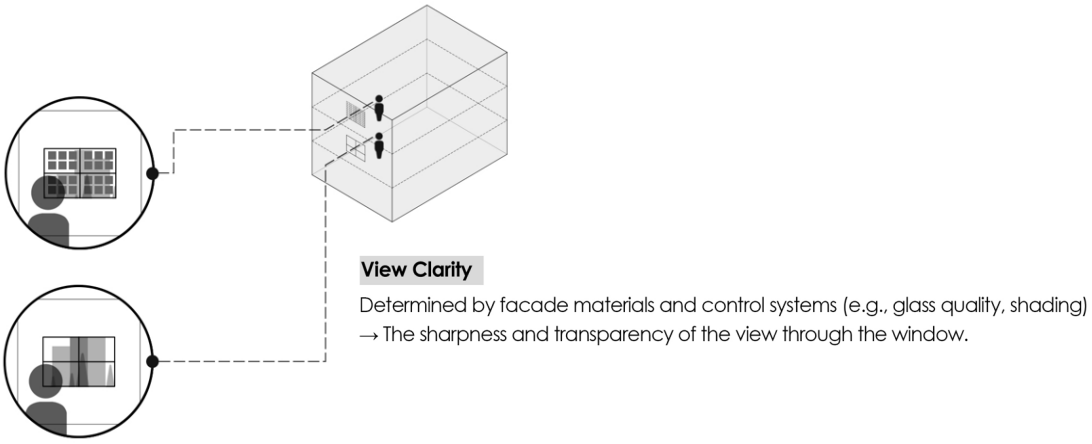


Figure 12. View privacy as subjectively Clarity by occupants, based on facade design (adapted from Ko et al. [62]).

The question asked: *"How satisfied/dissatisfied are you with the clarity of your window view* [93]*?"*.

View clarity is important as it directly influences overall satisfaction with the view quality. According to Konstantzos et al., clarity significantly impacts occupants' ability to perceive and enjoy external environments through glazing systems, and various glazing and shading configurations can considerably alter this clarity [42]. Ko et al. emphasize that view clarity encompasses window design, glazing materials, visual acuity, contrast sensitivity, and color perception, all critical for maintaining visual comfort and satisfaction [43].

View Privacy (Figure 13): The view privacy question assesses the occupants' perceived privacy offered by the window, an essential aspect of comfort in workplaces.

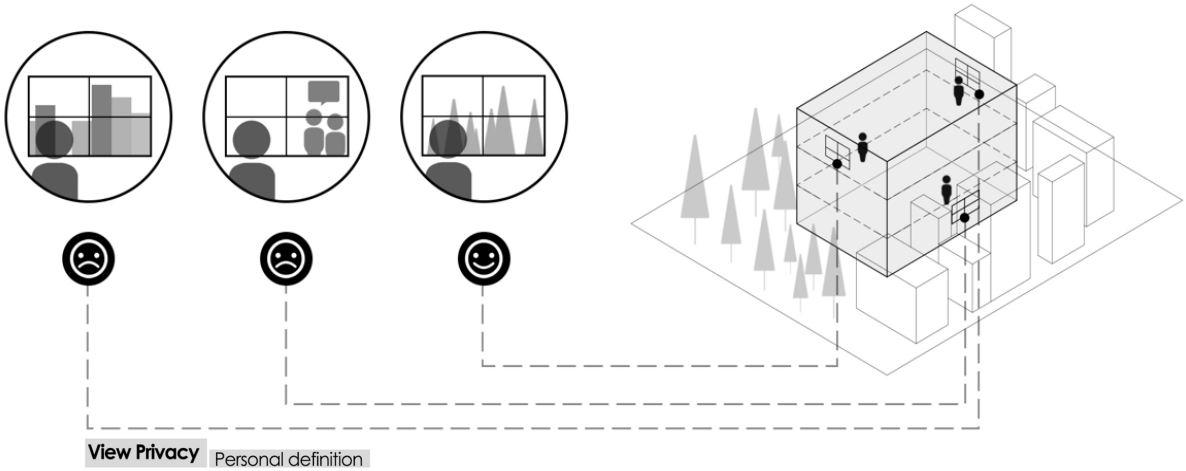


Figure 13. View privacy as subjectively perceived by occupants, based on outdoor content through different BIPV window configurations in the virtual office setting (adapted from Ko et al. [62]).

The question asked: *"How satisfied/dissatisfied are you with the level of view privacy through the window* [93]*?"*

Privacy influences occupants' sense of security and comfort, directly affecting their satisfaction and acceptance of window view. Ko et al. highlight that privacy considerations significantly influence occupant preferences, particularly in open-plan office layouts where visual distractions can impact productivity and satisfaction [44]. Therefore, evaluating view privacy is important for understanding and improving the user experience of window designs. In this experiment, window view privacy refers to participants' perceived likelihood of being seen from outside through the window. To isolate design effects, the exterior view content was held constant across all conditions (same scene, angle, distance, and activity), so any change in privacy judgments arises from BIPV design variables, specifically solar cell size and TVIS, rather than from differences in what is outside the window.

Overall Satisfaction: This question captures occupants' general satisfaction, integrating all specific visual quality dimensions such as clarity, color accuracy, privacy, and aesthetic enjoyment into one assessment. The question asked: *"Considering everything, how satisfied/dissatisfied are you with your overall window view?* [93]*"*.

Overall satisfaction is important because it combines multiple factors into a single measure, giving a clear summary of user experience [112]. This evaluation is essential to validate and summarize the effects of individual design parameters on user satisfaction and comfort.

4.2.5 Experimental Procedure

All participant sessions were scheduled between 10:00 am and 2:00 pm to ensure consistent indoor environmental conditions. The procedure for each participant followed a timeline, as illustrated in Figure 14.

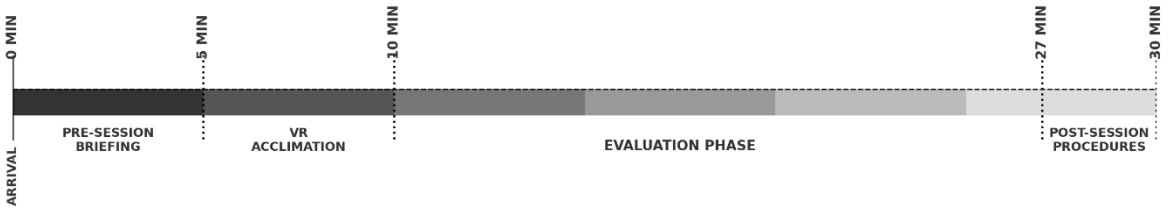


Figure 14. Timeline of a Single 30-Minute Experimental Session, showing the sequence and duration of events for each participant.

- Pre-Session Briefing and Arrival: Prior to their session, participants were invited via email and provided with instructions to familiarize themselves with the study objectives and procedures. Upon arrival, they received a structured instruction session clarifying the evaluation criteria, were informed about eligibility criteria, and provided written consent.
- IVR Acclimation: Following the briefing, participants wore the VR headset and were allowed 2-3 minutes to adjust comfortably to the virtual environment.

- Configuration Evaluation: After this acclimation period, participants evaluated each window configuration by answering three questions assessing view clarity, view privacy, and overall view satisfaction. To ensure accuracy, responses were verbally recorded by the researcher and immediately transcribed into an Excel file for data management.
- Post-Session Procedures: Upon completion of the evaluations, participants removed the VR headset and remained seated briefly to monitor for comfort. After confirming their well-being, the session was concluded. Participants subsequently received a follow-up email expressing gratitude for their participation.

Throughout the sessions, environmental conditions such as room temperature and humidity were recorded to maintain consistency. During the study period, the average room temperature was 23.2±0.8 °C (range: 22.1–24.5 °C, SD: 1.1), and the average relative humidity was 20.9±3% (range: 17.4–28.3%, SD: 3.8). The participant setup and testing procedures were consistent with the protocols established in the feasibility study (see Section 3.2.6).

4.2.6 Statistical Analysis Plan

To test the hypotheses, a series of statistical analyses was performed using R software (version 4.5). The plan was designed to select the appropriate statistical test for each research question.

- To test H_{2-1} and H_{2-2}(Effects of Cell Size and TVIS): Because these hypotheses examine differences in satisfaction ratings across multiple related configurations (a within-subjects design), the non-parametric Friedman Test was chosen. Where the Friedman Test revealed a significant overall difference, post-hoc Wilcoxon Signed-Rank tests with a Bonferroni correction were conducted for pairwise comparisons to identify which specific configurations differed from one another.
- To test H_{2-3} and H_{2-4} (Predictors of Satisfaction and Gender Effects): Because these hypotheses explore the predictive relationship between multiple variables, Ordinal

Logistic Regression (OLR) was used. This model is ideal for determining how predictor variables (view clarity, view privacy, BIPV configuration, and gender) influence an ordinal dependent variable (overall satisfaction). This analysis allows us to assess the relative importance of clarity and privacy (H_{2-3}) and to determine if gender acts as a significant moderating factor (H_{2-4}).

4.3 Results

4.3.1 Descriptive Statistics

This section summarizes the survey results from the study's two phases.

4.3.1.1 Phase 1

The descriptive statistics for Phase 1 summarize participant satisfaction ratings across three dimensions: view clarity, view privacy, and overall satisfaction, for three BIPV window configurations (3, 6, and 9). The mean and median ratings are presented in Table 7. Also, Figure 15 presents the distribution of these rating across configurations.

Table 7. Descriptive Statistics of Occupant Ratings for View Clarity, Privacy, and Overall Satisfaction across Different Window Configurations by Solar Cell Size (Phase 1)

Dimension		Mean	Median	SD
Clarity	Configuration 3(Full-size cell, TVIS=0.48)	1.20	1.50	1.40
	Configuration 6 (Half-size cell, TVIS=0.48)	0.25	0.00	1.41
	Configuration 9 (1/3-size cell, TVIS=0.48)	0.50	1.00	1.24
Privacy	Configuration 3 (Full-size cell, TVIS=0.48)	0.35	1.00	1.63
	Configuration 6 (Half-size cell, TVIS=0.48)	1.30	1.50	1.30
	Configuration 9 (1/3-size cell, TVIS=0.48)	1.60	2.00	0.99
Overall Satisfaction	Configuration 3 (Full-size cell, TVIS=0.48)	0.95	1.00	1.05
	Configuration 6 (Half-size cell, TVIS=0.48)	0.10	0.00	1.12
	Configuration 9 ((1/3-size cell, TVIS=0.48)	-0.35	-1.00	1.66

- **Configuration 3 (Full-size cell, TVIS=0.48)** received the highest view clarity rating (mean = 1.20). However, this configuration had the lowest view privacy rating (mean = 0.35). Despite the low privacy scores, it achieved the highest overall satisfaction rating (mean = 0.95), emphasizing the importance of clarity in overall window-view evaluation.
- **Configuration 6 (Half-size cell, TVIS=0.48)** showed moderate view clarity ratings and significantly higher view privacy ratings. Its overall satisfaction ratings were relatively neutral (mean = 0.10), suggesting a balanced but not highly preferred view quality experience.
- **Configuration 9 (One-third size cell, TVIS=0.48)** achieved the highest privacy ratings of the three configurations. However, it also received the lowest overall satisfaction

scores (mean = -0.35), underscoring that while privacy was enhanced, the increased view obstruction negatively impacted participant satisfaction.

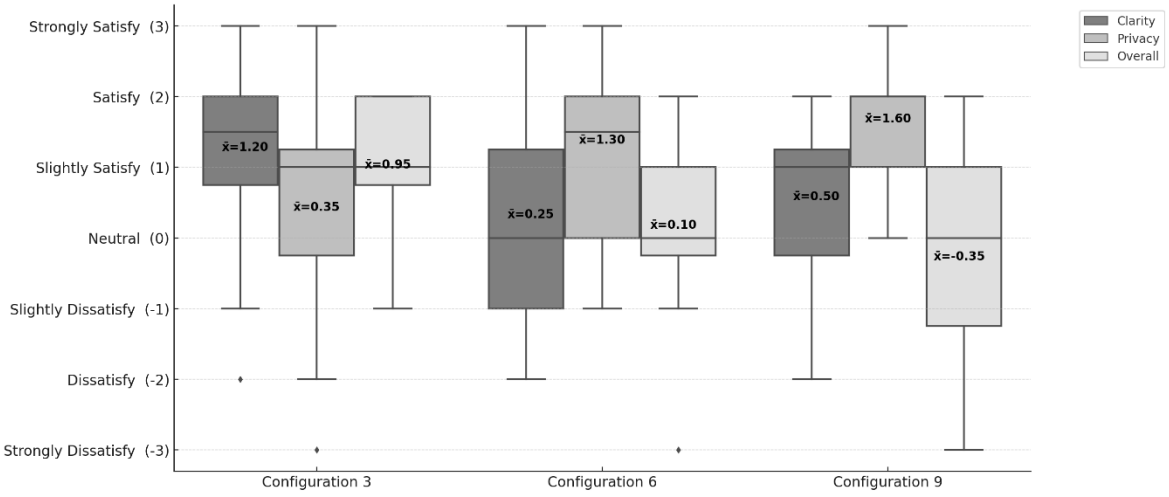


Figure 15. Distribution of Participant Satisfaction Ratings in Phase 1, by Cell Size (Full-Cell size, Half-Cell size and 1/3-Cell Size). Ratings were given on a 7-point scale from -3 (Very Dissatisfied) to +3 (Very Satisfied)

4.3.1.2 Phase 2

The descriptive statistics for Phase 2 summarize occupant satisfaction, evaluated for four BIPV window configurations: a Clear Window and three BIPV configurations (1, 2, and 3) with varying TVIS levels. The mean and median ratings are presented in Table 8 and visualized in Figure 16.

Table 8. Descriptive Statistics of Occupant Ratings for View Clarity, Privacy, and Overall Satisfaction across Different Window Configurations by TVIS Level (Phase 2)

Dimension		Mean	Median	SD
Clarity	Clear Window	2.38	3	1.23
	Configuration 1 (Full-size cell, TVIS=0.24)	-1.75	-2	1.33
	Configuration 2 (Full-size cell, TVIS=0.37)	0.93	1	1.07
	Configuration 3 (Full-size cell, TVIS=0.48)	2.33	2	0.57
Privacy	Clear Window	0.03	0	2.39
	Configuration 1 (Full-size cell, TVIS=0.24)	2.30	2.5	0.85
	Configuration 2 (Full-size cell, TVIS=0.37)	1.30	1	1.32
	Configuration 3 (Full-size cell, TVIS=0.48)	1.00	1	1.84
Overall Satisfaction	Clear Window	2.10	2.5	1.17
	Configuration 1 (Full-size cell, TVIS=0.24)	-0.83	-1	1.50
	Configuration 2 (Full-size cell, TVIS=0.37)	1.10	1	1.05
	Configuration 3 (Full-size cell, TVIS=0.48)	1.83	2	1.15

- **The Clear Window** received the highest clarity rating (mean = 2.38) and a very high overall satisfaction rating (mean = 2.10). As expected, it scored the lowest in privacy satisfaction.
- **Configuration 1 (lowest TVIS = 0.24)** received the lowest clarity ratings (mean = -1.75), indicating significant dissatisfaction due to obstructed views. Conversely, it had the highest privacy ratings (mean = 2.30), but its overall satisfaction was negative (mean = -0.83).

- **Configuration 2 (moderate TVIS = 0.37)** showed moderate clarity and good privacy, resulting in positive overall satisfaction ratings (mean = 1.10) and indicating a balanced compromise between clarity and privacy.
- Finally, **configuration 3 (highest TVIS = 0.48)** received clarity and overall satisfaction ratings that closely approached those of the Clear Window, with slightly lower privacy ratings. This indicates a strong occupant preference due to high clarity without significantly sacrificing privacy compared to the other BIPV options.

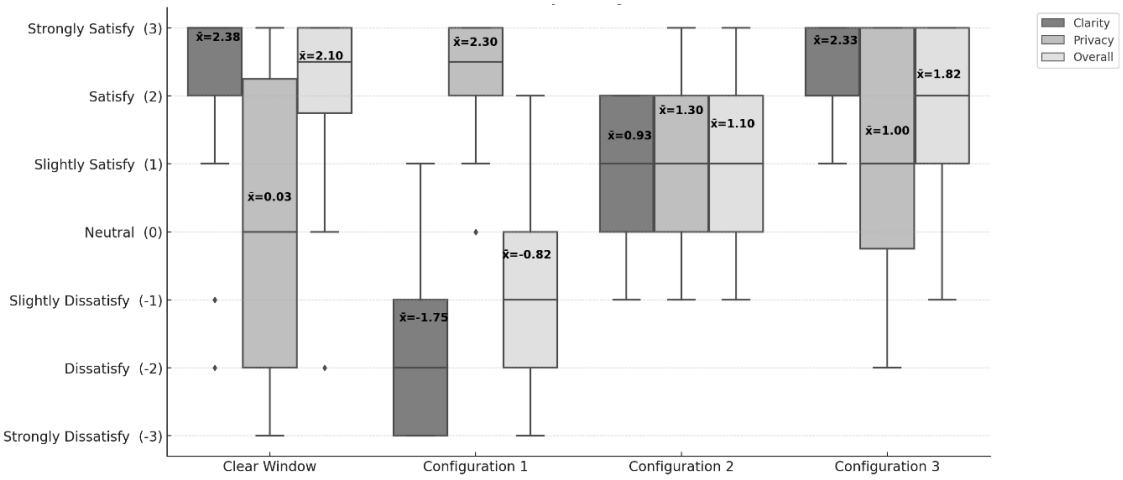


Figure 16. Distribution of Participant Satisfaction Ratings in Phase 2, by TVIS Levels (0.26, 0.37, and 0.48). Ratings were given on a 7-point scale from -3 (Very Dissatisfied) to +3 (Very Satisfied)

4.3.2 Statistical Analysis

4.3.2.1 Results for Hypothesis H_{2-1} : Effect of Solar Cell Size on View Clarity, Privacy, and Overall Satisfaction

Hypothesis H_{2-1} examined whether variations in solar cell size significantly influence occupant satisfaction of view clarity, view privacy, and overall satisfaction. To test this, participant ratings for Configurations 3 (full cell), 6 (half cell), and 9 (third cell), all with the same TVIS level

(0.48), were compared using the Friedman test, followed by Wilcoxon pairwise comparisons with Bonferroni correction.

As summarized in Table 9 the Friedman Test indicated:

- **View Clarity:** The results showed no statistically significant difference among the configurations ($\chi^2 = 5.303$, df = 2, p-value = 0.071).
- **View Privacy:** The results showed a statistically significant difference among the configurations ($\chi^2 = 14.25$, df = 2, p-value < 0.001).
- **Overall Satisfaction:** the results also showed a statistically significant difference among the configurations ($\chi^2 = 12.636$, df = 2, p-value = 0.002).

Table 9. Friedman test results for view clarity, privacy, and overall satisfaction across Cell Sized.

Dependent Variable	Chi-square (χ^2)	Degrees of freedom	p-value	Effect size (W)	Interpretation
View Clarity	5.303	2	0.071	0.13	No significant difference (p = 0.071 ≥ 0.05)
View Privacy	14.25	2	0.0008	0.36	Strong effect; significant differences among configurations
Overall Satisfaction	12.636	2	0.002	0.32	Moderate effect; significant differences among configurations

Post-hoc Wilcoxon pairwise comparisons were performed with Bonferroni correction. This test was selected to identify which pairs of configurations (3, 6, and 9) differed significantly. Table 10 summarizes the results of Wilcoxon Pairwise Comparisons (with Bonferroni correction).

Table 10. Wilcoxon Pairwise Comparisons (Bonferroni-corrected) for view privacy and overall satisfaction across different Solar Cell Sizes.

Comparison	View Privacy			Overall Satisfaction			Interpretation
	Adjusted p-value	z-value	Effect size (r)	Adjusted p-value	z-value	Effect size (r)	
C3 vs. C6	0.0036	-3.92	0.88	0.034	-3.57	0.80	Significant difference in both privacy and satisfaction
C3 vs. C9	0.0277	-3.51	0.78	0.011	-3.19	0.71	Significant difference in both privacy and satisfaction
C6 vs. C9	1	-2.67	0.60	0.824	-2.17	0.48	No significant difference in either privacy or satisfaction

Post-hoc Wilcoxon signed-rank tests revealed:

- Configuration 3 was rated significantly higher in overall satisfaction than Configuration 6 ($p = 0.034$) and Configuration 9 ($p = 0.011$).
- Configuration 3 was rated significantly lower in privacy than both Configuration 6 ($p = 0.0036$) and Configuration 9 ($p = 0.0277$).
- No significant differences were observed between Configurations 6 and 9 for either privacy or satisfaction.
- Differences in view clarity between configurations were not statistically significant.

These results partially support Hypothesis H_{2-1}. While solar cell size had no statistically significant effect on view clarity at the $p < 0.05$ threshold, it did significantly influence occupant

ratings of privacy and overall satisfaction. Configuration 3 (with full-size cells) was preferred overall, despite providing the lowest privacy, suggesting that a less obstructed view outweighed privacy concerns in occupant evaluations.

4.3.2.2 Results for Hypothesis H_{2-2} : Effect of TVIS Level on View Clarity, Privacy, and Overall Satisfaction

Hypothesis H_{2-2}. explored whether variations in TVIS significantly impact occupant perceptions of view clarity, view privacy, and overall satisfaction. This was assessed in Phase 2 using participant ratings across four configurations: a clear reference window and three BIPV windows (Configurations 1, 2, and 3), each with the same cell size but different TVIS values (0.256, 0.368, and 0.479).

As summarized in Table 11, the Friedman test revealed statistically significant differences across the configurations for all three dependent variables:

- **View Clarity:** The results showed a statistically significant difference among the configurations ($\chi^2 = 95.51$, df = 3, p-value < 0.001).
- **View Privacy:** The results showed a statistically significant difference among the configurations ($\chi^2 = 36.41$, df = 3, p-value < 0.001).
- **Overall Satisfaction:** The results also showed a statistically significant difference among the configurations ($\chi^2 = 67.13$, df = 3, p-value < 0.001).

Table 11. Friedman test results for view clarity, privacy, and overall satisfaction across TVIS levels.

Dependent Variable	Chi-square (χ^2)	Degrees of freedom	p-value	Effect size (W)	Interpretation
View Clarity	95.51	3	< 2.2e–16	0.796	Significant differences among configurations; Strong effect.
View Privacy	36.41	3	6.13e–08	0.303	Significant differences among configurations; Moderate effect.
Overall Satisfaction	67.13	3	1.76e–14	0.559	Significant differences among configurations; Substantial effect.

To further identify where differences occurred, Wilcoxon signed-rank tests with Bonferroni correction were conducted (See Table 12a and b). Key findings include:

- **Clarity and Satisfaction:** The Clear Window was rated significantly higher than Configurations 1 and 2 ($p < 0.001$ and $p = 0.005$). No significant difference was observed between the Clear Window and Configuration 3.
- **Privacy:** Configuration 1 (lowest TVIS) received the highest privacy ratings, significantly higher than the Clear Window and Configuration 3 ($p = 0.0001$ and $p = 0.021$, respectively).
- **Within BIPV Comparisons:** Configuration 3 was rated significantly higher than Configurations 1 and 2 in both clarity and overall satisfaction, while privacy differences were less pronounced.

Table 12a. Wilcoxon pairwise comparisons (Bonferroni-corrected) across TVIS configurations.

Comparison	View Clarity	View Privacy	Overall Satisfaction	Interpretation
	Adjusted p-value	Adjusted p-value	Adjusted p-value	
Clear vs C1	1.53e-10	0.0001	7.97e-07	Significant differences across all measures. p< 0.001
Clear vs C2	0.0002	0.0058	0.0051	Significant differences across all measures
Clear vs C3	1	0.021	0.9094	Significant for Privacy only
C1 vs C2	3.76e-07	0.0006	2.94e-06	Significant differences across all measures
C1 vs C3	1.09e-11	0.0055	3.53e-06	Significant differences across all measures
C2 vs C3	2.23e-06	1	0.0096	Significant for Clarity and Overall Satisfaction

All p-values were adjusted using Bonferroni correction based on six pairwise comparisons for each dependent variable (View Clarity, View Privacy, Overall Satisfaction). Thus, the adjusted significance threshold was $\alpha/6 = 0.05/6 \approx 0.0083$.

Table 13b. Wilcoxon pairwise comparisons (Bonferroni-corrected) across TVIS configurations (Effect Size).

Comparison	View Clarity		View Privacy		Overall Satisfaction	
	Z-value	Effect size (r)	Z-value	Effect size (r)	Z-value	Effect size (r)
Clear vs C1	-5.44	0.86	-5.24	0.83	-5.33	0.84
Clear vs C2	-4.44	0.70	-4.63	0.73	-4.54	0.72
Clear vs C3	-3.72	0.59	-4.38	0.69	-4.15	0.66
C1 vs C2	-5.51	0.87	-4.89	0.77	-5.43	0.86
C1 vs C3	-5.51	0.87	-4.54	0.72	-5.20	0.82
C2 vs C3	-5.51	0.87	-3.75	0.59	-4.15	0.66

These results support Hypothesis H_{2-2}. TVIS level had a significant impact on all three dimensions of occupant satisfaction. Specifically, higher TVIS values improved clarity and overall satisfaction, even if they slightly reduced perceived privacy. The findings suggest that participants preferred more transparent configurations, valuing external visibility over increased visual shielding.

4.3.2.3 Results for Hypotheses H_{2-3} Effect of View Clarity and Privacy as a predictor of Overall Satisfaction

Hypothesis H_{2-3} tested whether view clarity and view privacy significantly predict occupants' overall satisfaction with BIPV window configurations. To examine this, OLR models were applied separately to the Phase 1 and Phase 2 datasets.

In Phase 1, as shown in Table 13, view clarity was a significant positive predictor of overall satisfaction (β = 1.1351, p < 0.001), indicating that higher perceived clarity strongly increased satisfaction. In contrast, view privacy was not a significant predictor (β = 0.0444, p = 0.808). Among the configuration controls, Configuration C9 versus C3 had a significant negative effect on satisfaction (β = -1.9226, p = 0.008), suggesting that participants were less satisfied with more obstructed views, even when privacy was higher.

Table 14. Ordinal Logistic Regression Results – Phase 1: Effect of Solar Cell Size on Satisfaction Predictors

Predictor	Estimate (β)	odds ratio (OR)	p value	Interpretation
View Clarity	1.1351	3.11	<0.001	Significant Positive effect
View Privacy	0.0444	1.05	0.808	Not Significant
C6 vs C3	-0.976	0.38	0.142	Not Significant
C9 vs C3	-1.9226	0.15	0.008	Significant Negative effect

In Phase 2, results presented in Table 14 confirmed that both view clarity and privacy were statistically significant predictors of overall satisfaction. View clarity again emerged as the strongest predictor (β = 1.882, p < 0.001), while view privacy had a weaker but still significant positive effect (β = 0.389, p = 0.009). This indicates that while both factors contribute to satisfaction, clarity has a more dominant role in shaping occupant satisfaction. Additionally, Configuration 1 and Configuration 2 were rated significantly lower in satisfaction than the clear window, further emphasizing the importance of clarity.

Table 15. Ordinal Logistic Regression Results – Phase 2: Effect of TVIS Level on Satisfaction Predictors

Predictor	Estimate (β)	odds ratio (OR)*	p value	Interpretation
View Clarity	1.882	6.57	<0.001	Significant positive predictor
View Privacy	0.389	1.48	0.009	Significant positive predictor
Configuration 1 (vs Clear Window)	-3.412	0.033	<0.001	Significant negative predictor
Configuration 2 (vs Clear Window)	-1.330	0.26	<0.001	Significant negative predictor
Configuration 3 (vs Clear Window)	-0.350	0.70	0.297	Not significant

*OR = e^{β}

Together, these results provide strong support for Hypothesis H_{2-3}, confirming that view clarity is a consistent and influential predictor of overall satisfaction across both phases. Privacy contributes positively but more modestly, particularly when clarity is preserved. These findings

highlight the importance of optimizing TVIS in BIPV window design to enhance occupant comfort and satisfaction.

4.3.2.4 Results for Hypotheses H_{2-4}: Effect of Gender as a Predictor of View Clarity, Privacy, and Overall Satisfaction

Hypothesis H_{2-4} examined whether gender significantly predicts occupant satisfaction with view clarity, view privacy, or overall satisfaction across BIPV window configurations. To assess this, OLR models were used in both Phase 1 and Phase 2, with gender included as a predictor.

As shown in Table 15, in both phases, gender was not a statistically significant predictor of overall satisfaction. In Phase 1, the effect of being male (versus female) had an estimate of β = -0.7816 ($p < 0.05$). While in Phase 2, the estimate was β = -0.226 ($p < 0.05$).

Table 16. Ordinal Logistic Regression Results for Gender Predictor Across Phases 1 and 2

Phase	Predictor	Estimate (β)	odds ratio (OR)	p value	Interpretation
Phase 1	Male vs. Female	-0.7816	0.46	0.157	Not Significant, $p < 0.05$
Phase 2	Male vs. Female	-0.226	0.80	0.397	Not significant, $p < 0.05$

While the regression results confirm no statistically significant effect, descriptive analyses in Table 16 (Phase 1) and Table 17 (Phase 2) provide additional context. In Phase 1, females consistently reported higher ratings than males for clarity and overall satisfaction across all three configurations, with the most pronounced difference in Configuration 3 (females: 1.5; males: 0.4). In Phase 2, this trend also appeared, particularly in the Clear Window and Configuration 3, where females again rated clarity and satisfaction higher than males.

Table 17. Mean Occupant Ratings of View Clarity, Privacy, and Overall Satisfaction by Gender Across BIPV Window Configurations 3, 6, and 9

Configuration	Gender	Mean Clarity	Mean Privacy	Mean Overall Satisfaction
Configuration 3	Male	0.7	0.5	0.4
	Female	1.7	0.2	1.5
Configuration 6	Male	-0.6	1.6	-0.3
	Female	1.1	1	0.5
Configuration 9	Male	0.1	1.4	-1
	Female	0.9	1.8	0.3

Table 18. Comparison of Mean Occupant Ratings for View Clarity, Privacy, and Overall Satisfaction by Gender Across Clear Window and BIPV Configurations 1, 2, and 3

Configuration	Gender	Mean Clarity	Mean Privacy	Mean Overall Satisfaction
Clear Window	Male	2.27	-0.68	1.91
	Female	2.50	0.89	2.33
Configuration 1	Male	-1.73	2.18	-0.68
	Female	-1.78	2.44	-1.00
Configuration 2	Male	0.95	0.77	1.05
	Female	0.89	1.94	1.17
Configuration 3	Male	2.18	0.59	1.77
	Female	2.50	1.50	1.89

However, these observed trends did not reach statistical significance in the regression models and thus cannot be interpreted as meaningful predictors. Although not statistically significant in the overall models, these variations suggest that future research with a larger sample could explore potential nuanced interactions between gender and specific BIPV design configurations.

These results indicate that gender did not significantly influence how participants rated view clarity, privacy, or overall satisfaction with BIPV window views in this study. While descriptive statistics may have shown minor variations in ratings by gender, such differences were not statistically significant in the regression models.

Therefore, Hypothesis H_{2-4} is not supported. The results indicate that gender does not significantly affect occupant perceptions of view clarity, privacy, or overall satisfaction in this context. As such, gender-specific design strategies related to BIPV window views do not appear warranted based on the findings of this study.

4.4 Discussion

The following discussion is organized to directly evaluate each hypothesis based on statistical results.

4.4.1 Hypothesis H_{2-1}

This hypothesis, which explored how solar cell size affects occupant perceptions, was partially supported by the results. While the Friedman test found no statistically significant difference in view clarity ratings across the Phase 1 configurations (p = 0.071), it found significant differences for both view privacy and overall satisfaction

Participants preferred Configuration 3 (full-size cells) even though it offered the least privacy. This implies that occupants favoured the less cluttered view provided by the larger cells,

suggesting that the visual pattern of obstruction may be more influential on overall satisfaction than the level of privacy it affords.

While smaller cells may improve view privacy and produce more uniform patterns, results indicate they can also lead to a more fragmented and obstructed view experience. For the building industry, this highlights a potential disconnect between performance-driven optimization and user-centered perception: a design that technically offers more privacy may still be viewed as less desirable by occupants. As such, perceptual quality, especially the balance between openness and obstruction, should inform both product development and façade design workflows.

4.4.2 Hypothesis H_{2-2}

This hypothesis, which explored how TVIS level affects occupant perceptions, was fully supported by the results. The Friedman test revealed statistically significant differences in participant ratings across the four Phase 2 configurations, three BIPV windows with different TVIS levels (TVIS = 0.26, 0.37, 0.48) and one clear reference window (TVIS = 0.7), for all three evaluation criteria: view clarity ($\chi^2 = 95.51$, $p < 0.001$), view privacy ($\chi^2 = 36.41$, $p < 0.001$), and overall satisfaction ($\chi^2 = 67.13$, $p < 0.001$).

Participants preferred the clear window and Configuration 3 (TVIS = 0.48) even though these options offered lower privacy. This implies that occupants favoured configurations with higher TVIS, suggesting that the openness of the view may be more influential on satisfaction than the degree of visual shielding it provides.

While lower TVIS values may improve view privacy, this study shows they can also result in obstructed and less desirable views. Phase 2 findings indicate that participants favoured more transparent configurations, prioritizing visual openness over shielding. For the building industry, these findings point to a disconnect between optimizing for view privacy and aligning with occupant preferences. As such, perceptual quality, especially the balance between TVIS and shielding, should inform both product development and façade design workflows.

Prioritizing visual openness over maximum shielding may better reflect how occupants evaluate their everyday window experiences.

4.4.3 Hypothesis H_{2-3}

This hypothesis, which tested whether view clarity and privacy predict satisfaction with BIPV window views, was clearly supported by the results. Across both phases, view clarity emerged as the most influential factor shaping occupant satisfaction, with privacy contributing more modestly and inconsistently.

In Phase 1, satisfaction was driven almost entirely by clarity. Participants reported higher satisfaction when outward views were more legible, regardless of privacy levels. Privacy had no statistically significant effect, and configurations with increased visual obstruction were rated lower, even when they offered greater shielding.

Phase 2 reinforced these findings. While both clarity and privacy were statistically significant, clarity remained the stronger predictor by a wide margin. This suggests that user evaluations of BIPV window performance are shaped primarily by how well the view supports openness, depth, and connection, rather than how concealed the interior space feels.

For design, these results point to a clear priority: BIPV windows should emphasize TVIS to enhance user satisfaction. While privacy may still play a role in specific contexts, it does not appear to compensate for diminished clarity in most environments. Instead, design strategies should ensure that view quality remains perceptually open, particularly in spaces where comfort and visual access are linked.

4.4.4 Hypothesis H_{2-4}

Examining Hypothesis H_{2-4} which exanimated whether gender would influence how occupants are satisfied with view clarity, privacy, and overall satisfaction with BIPV window views. However, the analysis found no statistically significant gender effect, which must guide both interpretation and application. While minor descriptive differences were observed across configurations, particularly in the higher clarity and satisfaction scores reported by female

participants, these trends did not reach statistical significance and should not be interpreted as meaningful or generalizable effects.

This outcome reinforces a critical principle in evidence-based design: design decisions should not be based on demographic assumptions without robust statistical support. Although it might be tempting to infer gender-specific preferences from small observed differences, doing so risks overfitting design solutions to patterns that may not hold at scale. In this study, the absence of a measurable gender effect suggests that the core visual experience offered by BIPV windows, view clarity, view privacy balance, and overall view satisfaction is interpreted similarly across male and female users, at least within the context and sample used.

In summary, Hypothesis H_{2-4} is not supported, and its rejection carries a useful design insight: BIPV window views were experienced in statistically similar ways across gender, making clarity, not user identity, the more reliable predictor of satisfaction in this context.

4.5 Limitations

This study's findings are constrained by several limitations inherent to its design and methodology. Firstly, the results are based on specific BIPV window configurations and limited to the sample demographics employed in this thesis, which may not represent broader population dynamics. Additionally, the experimental setting and simulation environment used may differ significantly from real-world conditions, potentially influencing occupants' satisfaction ratings. Furthermore, the sample size and characteristics, including cultural context, age, and occupational background of participants, limit generalizability. Therefore, conclusions should be cautiously applied within the specific criteria and contexts established in this research, highlighting the need for further studies across diverse demographics, real-world settings, and additional configurations to enhance the robustness and external validity of the results.

Chapter 5

Complementary Energy & Daylighting Analysis of Optimal BIPV Configurations

5.1 Introduction

In chapter 4, the relationship between solar cell size and TVIS of BIPV windows was investigated to identify occupant satisfaction in terms of view clarity and privacy. While these visual and experiential aspects are essential for user comfort and acceptance, they capture only a portion of the overall performance of BIPV windows. Chapter 5 broadens the scope of analysis by incorporating assessments of annual renewable energy yield and daylight performance, emphasizing the need to evaluate BIPV windows as integrated, multifunctional façade elements. Estimating energy yield reveals the system's role in enhancing building energy efficiency and lowering carbon emissions, while daylight performance influences indoor illumination, occupant well-being, and opportunities to reduce reliance on artificial lighting. Considering these additional performance characteristics enables a more comprehensive understanding of BIPV window effectiveness, balancing energy generation with visual quality and user experience, leading to more informed, sustainable design decisions.

This chapter aims to evaluate the energy and daylight performance of two selected BIPV window configurations. Building on the occupant satisfaction findings from Chapter 4, which indicated a preference for larger solar cells and higher TVIS, Configuration 3 (Full-cell, TVIS = 0.479) was identified as offering an optimal balance between view clarity, privacy, and overall user satisfaction. Configuration 2 (Full-cell, TVIS = 0.368) was also chosen as an alternative design option, as it demonstrated similarly high levels of occupant approval. For comparative purposes, a clear reference window (TVIS = 0.702) will be used as the baseline to contextualize the performance of the two selected BIPV configurations.

The following research questions are proposed to guide this complementary BIPV window study.

- What is the potential renewable energy generation of occupant-preferred BIPV window configurations for an office building façade in the city of Toronto?
- How do BIPV window configurations with moderate TVIS compare to clear glazing in maintaining high daylight autonomy?
- Can occupant-preferred BIPV window configurations effectively reduce the likelihood of glare and the need for internal shading devices while preserving access to window views?

5.2 Overview of the Simulation Methodology

The following sections provide an overview of the simulation methodology deployed to assess the electricity generation and daylight performance of BIPV window configurations. The daylight assessment was carried out using two key performance metrics: Daylight Autonomy (DA) and Daylight Glare Probability (DGP) [113], which together offer insights into both the energy efficiency and visual comfort associated to the selected BIPV designs.

5.2.1 Estimation of Renewable Electricity Generation

The normalized energy generation (per BIPV façade surface area, in W/m^2) for the selected BIPV window configurations was calculated using the temperature-corrected power output equation provided in the ASHRAE Handbook [114], for each hour of a typical meteorological year (TMY), for the City of Toronto (i.e., CAN_ON_Toronto.City-Univ.of.Toronto.715080_TMYx.2004-2018) ensuring statistically accurate representation of local climatic conditions.

$$P_{BIPV} = \eta\ [1+\mu_{P,mp}\ (t_{cell} - t_{ref})]\ I \qquad (W/m^2) \qquad (7)$$

This equation accounts for key parameters affecting photovoltaic module performance (P_{BIPV}), including BIPV window electrical efficiency (η), temperature coefficient ($\mu_{P,mp}$), operating cell temperature (t_{cell}), reference temperature ($t_{ref} = 25℃$) and plane-of-array (POA) irradiance (I). The t_{cell} was determined as follows:

$$t_{cell} = [e^{(a+bUmet)}] + t_a + (\frac{I}{I_{ref}})\Delta t \quad (°C) \quad (8)$$

where for a double-glazed BIPV window with low emissivity coating (surface 2 or 3), a = –2.85, b = –0.0351 (m/s) $^{-1}$ and Δt = 9℃. The t_a corresponds to the ambient dry bulb temperature (°C) and Umet to the wind speed (m/s) from the TMY file, and I_{ref} = 1000 W/m^2.

The POA irradiance was estimated for every hour of the year using the System Advisor Model (SAM), a software developed by the U.S. National Renewable Energy Laboratory (NREL) [115]. SAM deploys the Perez sky model, which accurately characterizes the distribution of diffuse solar radiation under various sky conditions. The Perez model considers both direct and diffuse (sky and ground) components, enabling more realistic simulations of solar irradiance on tilted surfaces [116]. Since the BIPV windows were vertically integrated on an office building façade, a tilt angle of 90 degrees was applied. Simulations were performed for multiple façade orientations including south, east, west, and intermediate angles, reflecting realistic building scenarios. In these simulations, the ground-reflected component (albedo) was assumed to be 0.2, representing typical urban surfaces such as concrete or mixed vegetation.

For monocrystalline silicon BIPV window technology, a reference cell efficiency of 22% was assumed representing typical cell efficiency available in the market. This resulted in BIPV window efficiency of η = 10.5% for Configurations 2; and η = 7% for Configurations 3. Also, a temperature coefficient of $\mu_{P,mp}$ = –0.453%/°C was assumed, representative for monocrystalline silicon cell technologies [114].

To estimate the AC generation, additional performance parameters were considered, based on ASHRAE guidelines, such as AC wiring losses (1%), and DC losses (module mismatch 2%,

diodes and connections 0.5%, DC wiring 2%). The normalized AC energy generation was then estimated:

$$E_{AC} = (1 - EL) \cdot \sum_{t=1}^{8760} \frac{(P_{BIPV} \cdot 1h)}{1000} \qquad \left(\frac{kWh}{m^2}\right) \qquad (9)$$

The total electric loss factor was calculated as follows:

$$EL_{total} = 1\text{-}[(1\text{-}EL_1)\cdot(1\text{-}EL_2) \cdot \ldots \cdot (1\text{-}EL_i)] = \approx 0.054 \qquad (10)$$

where EL_i = electric losses due to factor *i* such as AC wiring losses and DC losses. No shading was considered in this study.

Note that the electricity generation results presented in this study are normalized per BIPV facade surface area in kWh/m^2. This approach allows for an objective assessment of system performance independent of the total size of the installation. Unlike total energy output (in kWh), which is influenced by the facade's overall area, normalizing by façade surface area provides a clear metric of energy production per unit area. This is essential for comparing different BIPV technologies, orientations, and design configurations. It also facilitates benchmarking across BIPV studies and ensures that findings are scalable and transferable to different building contexts, enhancing their relevance for future applications and studies.

5.2.2 Daylighting and Glare Simulations

Annual daylighting simulations were conducted deploying Rhinoceros 7 for geometric modeling and ClimateStudio 2024 using Daysim (based on Radiance) as the engine. Daysim is a validated daylight simulation tool [117].

Similar to before, the analysis was performed for Configuration 3 (Full-cell, TVIS = 0.479) and Configuration 2 (Full-cell, TVIS = 0.368). For comparative purposes, a conventional double-glazed clear window (TVIS = 0.702) was also analyzed. The optical properties of all surfaces were maintained identical to the ones presented under the IVR study, under chapter 3.

The daylight performance metrics used are spatial Daylight Autonomy (sDA), and Daylight Glare Probability (DGP). For sDA, the target workplane illuminance was set at 300 lux, aligning with LEED v4 guidelines [118]; A point in the workplane is considered "daylit" if daylight illuminance meets or exceeds 300 lux for 50% of the annual occupied hours (i.e., sDA300,50%). The workplane grid analysis was set to 1 m by 1 m.

DGP was calculated for all occupied hours of the year (8:00 AM–6:00 PM with Daylight Saving Time), using a seated occupant viewpoint perpendicular to the window, at eye level of 1.20 m. This orientation was chosen to simulate a typical working posture facing the task area near the window, where glare risk is most prominent due to direct daylight exposure. It also aligns with the experimental setup: although participants were free to explore different viewing angles, nearly all chose to assess the view while seated perpendicular to the window, confirming this as the most representative occupant position. The spatial Disturbing Glare (sDG) was reported for the whole office space (not just the desk location), representing the percentage of occupied floor area where disturbing or intolerable glare (DGP > 38%) occurs during at least 5% of occupied hours, based on hourly DGP values from four view directions, including views both parallel and perpendicular to the façade.

This orientation was selected based on participant behaviour during the immersive window view evaluation. Although participants were free to explore various angles, the overwhelming majority (100%) naturally chose a direct, perpendicular viewing direction when assessing the view. This setup also represents a conservative, worst-case scenario for glare analysis, as direct exposure to the window maximizes luminance contrast and potential visual discomfort. Accordingly, using this viewpoint provides a rigorous assessment of glare risk under realistic yet demanding conditions.

Simulations were performed with and without interior shading devices to provide insights about visual comfort and daylight sufficiency. The shading device considered was a manually operable fabric roller shade (i.e., SWC M65, TVIS = 9.6%), that was deployed only during excessive discomfort (DGP > 0.4 or when horizontal illuminance at the eye exceeded 1000 lux).

Annual hourly simulation analysis was performed for occupied hours for a full calendar year at the City of Toronto, using the same meteorological file as the one used in the energy analysis.

5.3 Potential Electricity Generation Results and Comparative Analysis

The annual electricity generation potential of the BIPV windows varied across the two configurations, with C2 consistently producing more energy than C3 across all orientations (see Figure 17), due to higher window electrical efficiency, which is inversely proportional to window transmittance. On a south-facing façade, C2 achieved the highest yield at 93.0 kWh/m^2.year, whereas C3 generated only 62.0 kWh/m^2. year, reflecting a 33% reduction in annual energy production. This performance gap remained consistent across all orientations, with C2 outperforming C3 by margins ranging from 18% to 34%, depending on the façade direction. For example, on the east façade, C2 produced 75.9 kWh/m^2.year compared to 50.6 kWh/m^2.year for C3; on the southwest, the estimated potential generation is 91.0 versus 61.2 kWh/m^2.year, respectively. To contextualize these values, consider a 1,000 m^2 mid-rise office building with a south-facing BIPV façade. If C3 is installed, the facade would yield approximately 62,000 kWh/year, compared to 93,000 kWh/year if C2 were used instead. The 31,000 kWh/year difference between these configurations is substantial in a building context. For a comparison, a 1000 m^2 BIPV opaque rainscreen with a module efficiency of 21.5% will result in an estimated generation of 190,400 kWh/year.

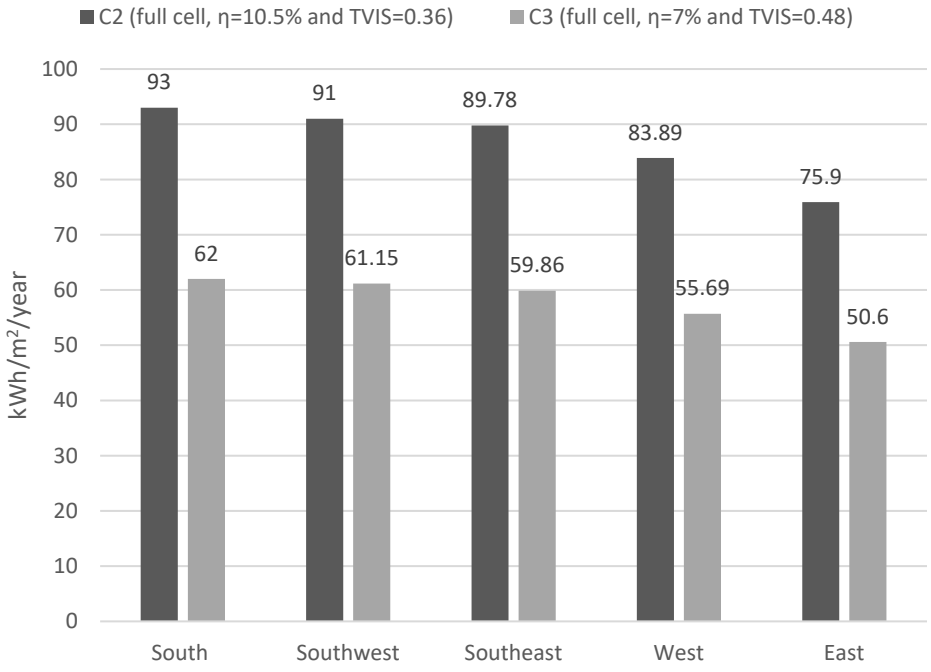


Figure 17. Potential Annual Energy Generation (kWh/m^2/year) for BIPV Window Configurations Across Different Façade Orientations.

The modest performance losses in east and west orientations (under 19% compared to south-facing) suggest that BIPV windows remain viable even for façades not facing directly south. This has meaningful implications for real-world applications where optimal orientation is not always achievable.

To illustrate seasonal dynamics, Figure 18 displays monthly potential electricity generation profiles for configurations C2 and C3 installed on a south-facing façade. Interestingly, energy generation peaks for both configurations during the months of March and September. This pattern, which contrasts with typical rooftop PV systems that peak in summer months, can be attributed to the sun's lower angle in winter and fall, resulting in higher plane-of-array (POA) irradiance on vertical surfaces.

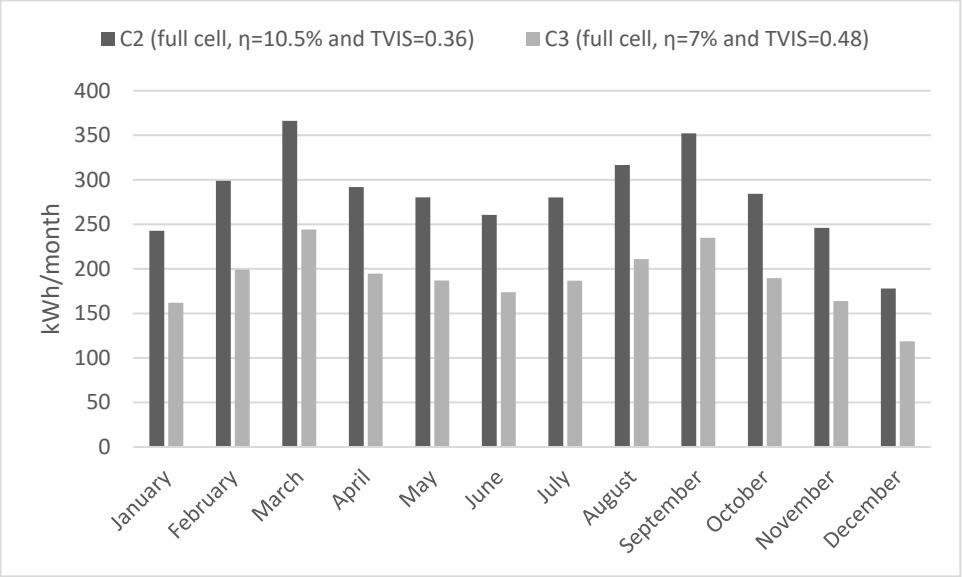


Figure 18. Monthly potential energy generation for C2 (left) and C3 (right) BIPV window configurations for a south-facing window.

5.4 Daylighting Simulation Results and Comparative Analysis

The unshaded clear double-glazed window (TVIS = 0.702) is considered as the baseline for daylight availability, glare risk, and view access in this simulation. The clear window, which has the highest TVIS in this study, consistently maximized daylight availability, recording 100% sDA300/50%, across all orientations (Table 18). However, this daylight benefit was accompanied by the highest glare risk. Table 19 shows that the percentage of occupied hours with sDG occurred on more than 50% of the occupied floor area for at least 5% of the occupied hours on most façades, including 53.6% on the south façade and 56.3% on the southwest façade for the clear window. Regarding view access, the clear glazing initially offers uninterrupted views, but when shading is introduced for glare mitigation, that advantage diminishes. Applying interior roller shades substantially reduced visual discomfort. For example, sDG on the southeast dropped from 52.2% to 30.4%, and from 44.0% to 26.6% on

the east. However, shading also introduced new drawbacks. View access was significantly impaired: shades were closed during 63.4% of occupied hours on the south and 48.7% on the west (Table 20). The impact on daylight autonomy was relatively modest; for instance, on the south façade, sDA decreased from 100% to 96.4%, and on the southeast façade, it remained unchanged at 100%. Overall, the clear window without shading delivers the highest possible daylight availability and full outside visibility, but at the cost of frequent glare. With shading, sDG is reduced by up to 29.7 percentage points, but this comes with a 3.6% drop in sDA and extensive obstruction of views, up to 63% of the time. These results highlight the trade-off between glare control and maintaining open, unobstructed views, reinforcing the importance of designing facades that can address both.

Table 19. Spatial Daylight Autonomy Comparison for sDA300/50%

Orientation	Roller Shading Status	Clear Window	C2	C3
East	No Shading	100%	100%	100%
	With Shading	100%	69.6%	93.8%
Southeast	No Shading	100%	100%	100%
	With Shading	100%	67.9%	86.6%
South	No Shading	100%	100%	100%
	With Shading	96.4%	54.5%	67.9%
Southwest	No Shading	100%	100%	100%
	With Shading	99.1%	62.5%	85.7%
West	No Shading	100%	100%	100%
	With Shading	100%	66.1%	96.4%

Table 20. Percentage of Spatial Disturbing Glare (sDG) during Occupied Hours

Orientation	Roller Shading Status	Clear Window	C2	C3
East	No Shading	44.0%	25.9%	32.1%
	With Shading	26.6%	15.0%	19.4%
Southeast	No Shading	52.2%	32.8%	41.1%
	With Shading	30.4%	22.8%	27.0%
South	No Shading	53.6%	35%	41.1%
	With Shading	33.3%	23.9%	28.3%
Southwest	No Shading	56.3%	33.7%	42.4%
	With Shading	35.7%	19.9%	29.9%
West	No Shading	48.8%	27.7%	35.9%
	With Shading	26.8%	13.4%	20.5%

Table 21. Annual Percentage of Time Roller Shades Remained Open for Each Configuration

Orientation	Shading Control Strategy	Clear Window	C2	C3
East	Glare Control	68.4%	71.4%	70.4%
Southeast		51.3%	59.2%	55.8%
South		36.6%	47.0%	44.4%
Southwest		51.9%	58.9%	56.8%
West		69.6%	72.8%	72.7%

Configuration 2 (C2), the mid-TVIS BIPV window in this study, demonstrated strong daylighting performance and modest glare mitigation compared to the clear glazing baseline. Without shading, it achieved 100% sDA300/50% across all orientations, identical to the clear window (Table 18). However, it offered moderately improved glare performance due to its integrated photovoltaic pattern. Table 19 shows that sDG values dropped noticeably relative to the unshaded clear window. For example, on the east façade, glare decreased from 44.0% to 25.9%, and on the south façade, it decreased from 53.6% to 35.0%. When a roller shade was used, glare risk dropped even further. On the west façade, for instance, sDG was reduced from 27.7% to just 13.4%, outperforming the shaded clear glazing (26.8%) by a significant margin (Table 19). Yet because C2 provided inherent glare control, shading was required less frequently overall. Table 20 shows that shades were open 59.2% of the time on the southeast façade and 47.0% on the south façade, representing an improvement of 8% to 10% compared to the shaded clear window for those façade orientations. This suggests that C2 maintains higher view access across a range of orientations. Overall, C2 provides a compelling middle ground. Compared to the clear window, it substantially reduces glare both with and without shading, while preserving high daylight autonomy. Most notably, when used with shading, it maintains 8-10% more annual hours with unobstructed views, illustrating its value in reducing the reliance on view-blocking roller shades.

Configuration 3 (TVIS = 0.48), which had the highest visible light transmittance among the BIPV window options (though still lower than the clear glazing reference), performed closest to the clear glazing baseline in terms of daylight availability while also offering improved glare control. C3, with a visible light transmittance of 0.48, delivered strong daylight performance across all orientations. Without shading, it achieved 100% sDA300/50%, consistent with the clear glazing and C2 (Table 18). When shading was applied for glare control, C3 maintained high daylight autonomy, with sDA values ranging from 67.9% on the south to 96.4% on the west façade. This performance exceeded that of C2 under shading, which dropped to as low as 54.5%, and approached the baseline clear window performance in some orientations. These results demonstrate C3's ability to sustain effective daylight delivery even under glare control

conditions, offering a favourable balance between visual comfort and daylight access. This positions C3 as the best-performing BIPV window for daylight in southeast and west orientations. In terms of glare, the performance was mixed. Without shading, Configuration 3 provided moderate improvement over clear glazing, although not as significant as the lower-TVIS alternatives. On the west façade, for instance, sDG dropped from 48.8% (clear) to 35.9% with C3 (Table 19), indicating noticeable but limited improvement in glare risk. However, once interior shading was introduced, glare performance improved significantly, down to 20.5% on the west façade, better than the shaded clear window at 26.8%. This shows that Configuration 3, when paired with minimal shading, can effectively manage glare without overly compromising daylight. Configuration 3 also required less shading than the clear window, helping preserve outside views. Shades remained open for 72.7% of occupied hours on the west façade and 56.8% on the southwest (Table 20), compared to 69.6% and 51.9%, respectively, for the clear window. This means C3 reduced both glare and shading demand, enhancing access to unobstructed window views. In essence, C3 presents a favourable balance: it offers high daylight autonomy (just 6-13% lower than clear glass), moderate glare control, and significantly more hours of unobstructed view access, making it a strong candidate for visual comfort in view-sensitive façade zones.

Additionally, Figures 19, 20, and 21 present temporal distributions of daylight glare probability (DGP) categories throughout the year for a south-facing façade, using interior roller shades controlled for glare. The data is shown by hour of day and day of year for the Clear Window baseline, C2, and C3, respectively.

Across all cases, glare risk was most pronounced between 11:00 and 14:00, coinciding with peak solar exposure. The clear window experienced substantial visual discomfort, with an sDG of 33.3% and 5% of view hours falling within the intolerable category. C3 offered moderate improvement, reducing sDG to 28.3% and intolerable glare to 4%. C2 exhibited the most effective glare control, lowering sDG to 23.9% and intolerable glare to just 3%. Its better performance is attributed to its lower visible light transmittance and denser BIPV cell coverage, which filtered blocked sunlight more effectively. Moreover, C2 maintained a higher rate of

shading-free operation (47.0% blinds open), outperforming both C3 (44.4%) and C0 (36.6%), thereby enhancing view access while minimizing glare.

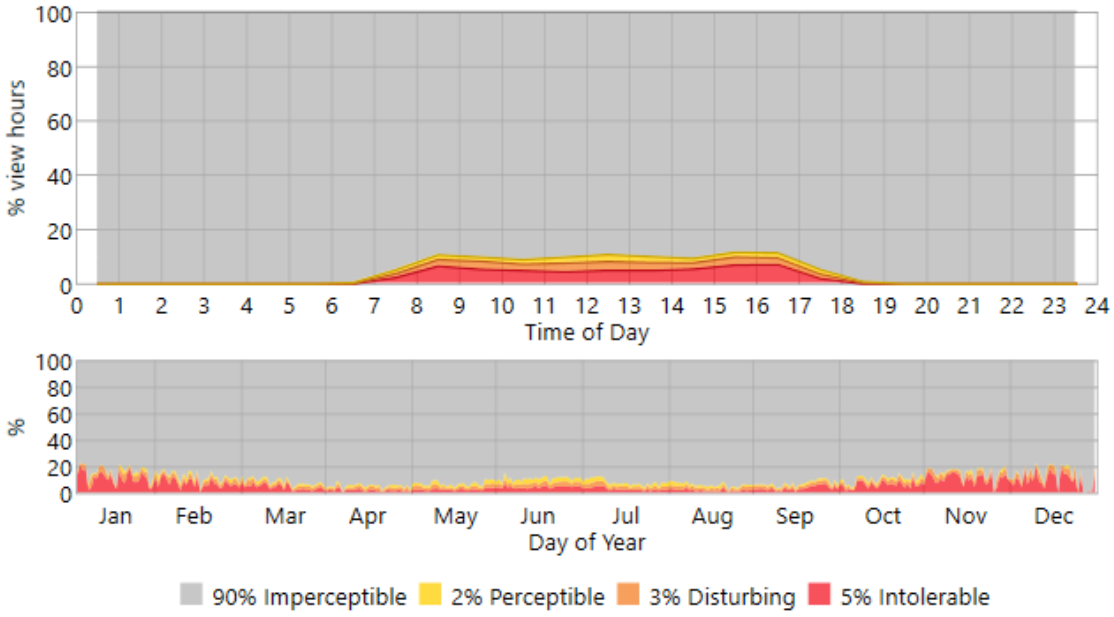


Figure 19. Annual sDG distribution and spatial glare map for the south-facing façade using the Clear Window with glare-controlled shading.

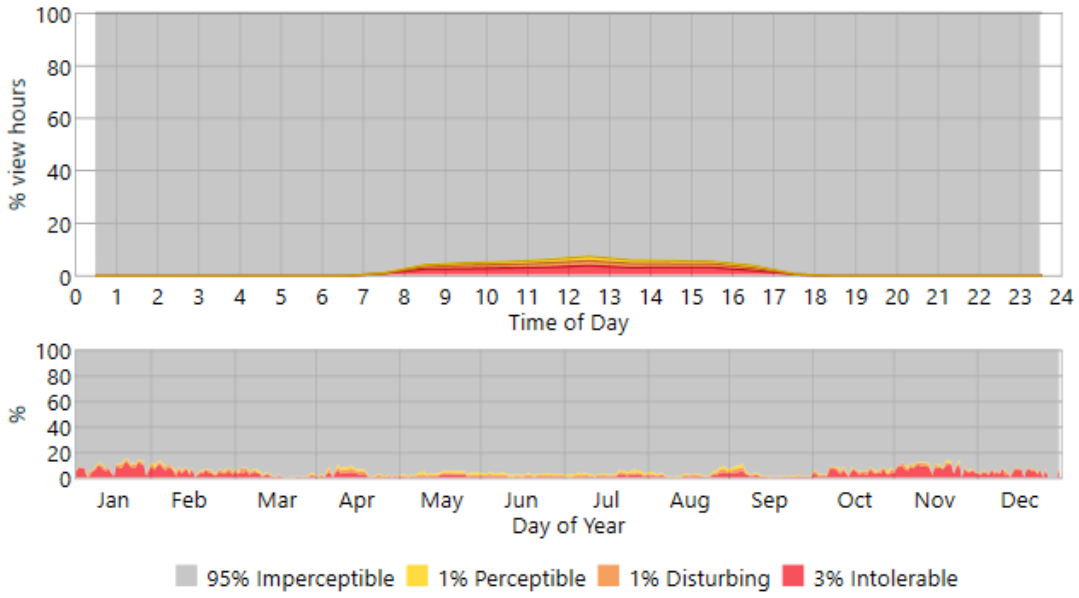


Figure 20. Annual sDG distribution and spatial glare map for the south-facing façade using the Configuration 2 (C2) with glare-controlled shading.

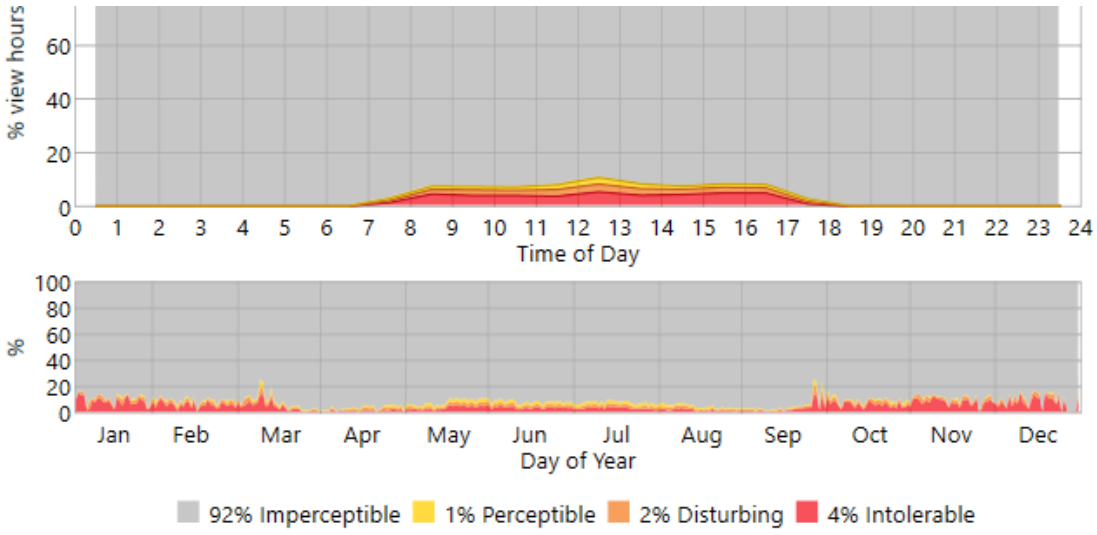


Figure 21. Annual sDG distribution and spatial glare map for the south-facing façade using the Configuration 3 (C3) with glare-controlled shading.

5.5 Chapter Summary

This chapter presented a comprehensive analysis of two BIPV window configurations (Configuration 2 and Configuration 3) compared to a conventional clear double-glazed window, across three core performance metrics: annual potential annual electricity generation, annual sDA, and sDG. Building on occupant satisfaction study from Chapter 4, the selected configurations were evaluated under multiple façade orientations using validated simulation tools and methods.

As expected, energy generation is inversely proportional to TVIS: Configuration 2 (TVIS = 0.37 and η = 7%) consistently demonstrates better performance than Configuration 3 (TVIS = 0.48 and η = 10.5%) across all orientations, with up to 33% more energy production on the south-facing façade. The C2 is the preferred BIPV solution for maximizing photovoltaic energy generation and minimizing glare. C3, while less efficient in energy production, provides superior daylight autonomy under glare-controlled conditions and enhances visual comfort by allowing the glare-controlled roller shades to remain open for slightly longer periods. Both configurations benefit from interior shading and should be selected based on orientation-specific priorities and user-centered performance criteria. A thoughtful combination of C2 and C3 across the building façade can provide a balanced strategy for energy efficiency, daylighting quality, visual comfort, and occupant satisfaction.

Chapter 6

Discussion & Final Conclusions

6.1 Synthesis of Results

This research combined immersive perception, human subject data, and building performance simulations to investigate how BIPV window configurations impact occupant experience and comfort. The study was structured in three interdependent parts: the first evaluated immersive Virtual Reality (IVR) as a research tool, the second captured subjective evaluations of window view quality, and the third assessed energy, daylight, and glare performance of user-preferred configurations. These components were designed to be complementary, underscoring the importance of evaluating occupant experience and building performance together rather than in isolation.

The first part (presented under Chapter 3) demonstrated that the immersive VR environment was effective in simulating spatial experience. Spatial presence received the highest participant ratings (i.e., mean value of 1.35 on a five-point scale ranging from -3 to 3), followed by involvement (i.e., mean value of 1.10) and realism (i.e., mean value of 0.90). The slightly lower realism scores were tied to early stage rendering limitations and VR system latency, which were addressed through hardware improvements and rendering refinement under part two of the study. By the end of the first phase, the system achieved sufficient perceptual fidelity to support the human-centered assessment of window view quality. The study results confirmed that immersive VR can be used as a credible tool to evaluate the impact façade design has on view quality during early-stage design, particularly in cases where physical prototyping is not feasible.

The second part of the study focused on how BIPV design variables, specifically solar cell size and visible light transmittance, affected occupant satisfaction with view clarity, view privacy, and overall perception. Across both experimental phases (of the second part of the study, presented under Chapter 4), view clarity consistently emerged as the dominant factor in

shaping overall satisfaction. Configuration 3, which used full-size solar cells and TVIS of 0.48, achieved the highest overall satisfaction score, even though it provided the lowest privacy among the BIPV configurations evaluated. Statistical analysis showed that clarity had a stronger and more consistent predictive relationship with overall satisfaction compared to privacy (i.e., $\beta = 1.88$ vs. $\beta = 0.39$, respectively; both significant). Configuration 2, which featured a mid-TVIS value (TVIS = 0.37), was rated high for clarity while still offering moderate visual privacy, making it the most preferred option overall. This dual advantage justified its selection for further simulation-based analysis in Part 3, where its energy, daylight, and glare performance were evaluated in comparison to the clear glazing baseline and Configuration 3. These results suggest that for most occupants, being able to see outside clearly was more important than maintaining visual privacy from others. Gender differences were observed descriptively but did not have a statistically significant influence.

The third part of the study tested whether those preferred configurations would still be effective from an energy and daylighting perspective. Simulations indicated that Configuration 3 (TVIS = 0.48 and $\eta = 7\%$), while delivering lower annual energy yield when compared to Configuration 2 (i.e., 62 kWh/m^2 per year for C3 vs 93 kWh/m^2 per year for C3, for an unobstructed south-facing façade in Toronto), resulted in higher daylight autonomy and more time with open roller shades. Configuration 3 performed well in most orientations, maintaining spatial daylight autonomy values above 85% and reducing shading system activation compared to clear glazing. Configuration 2 (with TVIS = 0.37 and $\eta = 10.5\%$), performed better in glare control and maintained higher visual comfort in orientations with intense solar exposure, such as south and southwest. These findings indicate that both configurations provide different strengths and should be selected based on the specific priorities of a given façade orientation.

The complete study reveals two key insights. First, occupant satisfaction with BIPV windows is most influenced by perceived clarity, across the tested TVIS range (0.37-0.48). While BIPV configurations with lower TVIS values offered greater view privacy, this factor had a weaker and less consistent impact on overall satisfaction. In other words, beyond a TVIS=0.37 of view clarity, additional gains in privacy did not significantly enhance occupant preference. Second,

preferences collected through immersive environments under this study align well with energy and daylight performance results. This means occupant perception might not be in opposition to sustainable performance but can be integrated into design decisions in a measurable way.

Overall, this research demonstrates that immersive evaluation can generate specific, predictive insights about BIPV window design. The approach allows design teams to quantify how solar cell patterns and TVIS levels will be experienced by future occupants while ensuring that preferred configurations also meet energy and daylight goals. This research do not generalize or speculate beyond their defined scope. Instead, it provides grounded evidence that view quality, and performance can be evaluated together, using tools that are accessible at the early stages of façade design.

6.2 Design Guidelines for BIPV Façade Selection

Within the context of this study, Configuration 2 (C2) should be prioritized in zones where energy production and glare reduction are critical, such as offices, classrooms, or spaces requiring privacy. C2 demonstrated strong glare mitigation and moderate view clarity, making it especially suitable for visually sensitive environments.

Configuration 3 (C3) is recommended for occupant-intensive zones where access to daylight and outside views enhances well-being and comfort. Its higher visible light transmittance delivered superior view clarity and high satisfaction ratings, despite offering less visual privacy.

While all configurations benefit from integrated shading, C2 was the most reliable for minimizing discomfort in high-exposure conditions. C3, meanwhile, offers a better connection to the outdoors. Though shade-open hours were similar between C2 and C3, view clarity was consistently higher in C3.

To maximize system effectiveness, operational strategies should account for seasonal PV variability and include automated shading and daylight-responsive lighting controls. This integrated approach supports both energy goals and visual comfort.

6.3 Contributions and Potential Implications

6.3.1 Major and Minor Contributions

Contributions are classified as major or minor based on their originality, practical relevance, and potential to shape future research or design practices.

6.3.1.1 Major Contributions

Establishing IVR as a Credible Method for BIPV Façade Evaluation: This study advances IVR from a visualization aid to a validated research method. By developing and testing a scalable IVR workflow, and confirming its realism and presence ratings with over 70 participants, the research demonstrates that IVR can reliably capture occupant perceptions of BIPV façade design. This contribution provides building scientists and designers with a validated, repeatable approach for integrating human experience into façade performance studies.

Human-Centric Performance Benchmarking for BIPV Window Design: Controlled experiments showed that view clarity is the main driver of occupant satisfaction, while privacy is less influential. A perceptual threshold was identified at TVIS = 0.37, below which satisfaction declined sharply. The most preferred option, TVIS = 0.48 with full cells, balanced clarity and shading, despite lower energy output.

Validation of Occupant-Preferred Designs Using Integrated Environmental Simulation: IVR-selected configurations were validated through annual energy and daylight simulations, demonstrating a strong alignment between clarity preferences and performance metrics, including high daylight autonomy, low glare (as assessed by Climate Studio), and reduced shade use. This confirms the credibility of immersive feedback for façade design.

A Decision Framework for Aligning Perceptual and Environmental Criteria in Façade Specification: By connecting occupant ratings with performance metrics, the study offers a repeatable framework for selection of BIPV windows. Designers can now use TVIS and PF targets informed by both user preferences and performance simulations, enabling occupant-centered, performance-based BIPV selection.

6.3.1.2 Minor Contributions

Gender Trends: Female participants slightly rated clarity and satisfaction higher, suggesting potential value in future demographic analysis.

Open Access Design Tables: Detailed configuration-level results (energy, glare, satisfaction) are shared for future reference.

Methodological Refinements: Practical adjustments to IVR protocols (wired setup, scene transitions, orientation period) enhanced participant comfort and replicability.

Multi-Criteria Trade-off Without Physical Mock-ups: Demonstrated that IVR enables perception-performance evaluation without material samples, reducing cost and time in façade research.

6.3.2 Potential Implications

For Architects and Façade Designers: A TVIS threshold of 0.37 was identified, below which satisfaction declined. Higher-TVIS configurations like C3 reduced shading needs (blinds open >70% of time). Designers can use metrics (e.g., sDA > 85%) to guide early decisions balancing comfort and performance.

For BIPV Manufacturers: Users preferred configurations with TVIS 0.37–0.48, offering clarity and visual uniformity. Less transparent options produced more energy but were less satisfactory for the occupants, making clarity a key design target.

For Simulation & Human Factors Researchers: IVR proved reliable for capturing perceptual feedback aligned with daylight, glare, and energy simulations. The workflow is adaptable to other façade systems like electrochromic or fritted glazing.

For Certification and Policy: Findings support daylight/view credits in LEED v4, WELL, and Green Globes. C2 and C3 met sDA > 85% with controlled glare.

6.4 Limitations

This study was designed to balance methodological innovation with practical constraints. While the findings are robust within the defined scope, several limitations should be acknowledged to contextualize their applicability.

Lack of Real-World Validation for Immersive Perception: Although the IVR environment achieved statistically significant scores for spatial presence and involvement, participants evaluated realism based on their general familiarity with real offices, not by directly comparing virtual and physical spaces. This limits claims about absolute perceptual accuracy and calls for future validation using side-by-side physical mockups or photometric calibration methods.

Short-Term Exposure and Controlled Viewing Conditions: Each participant engaged with the virtual window views for less than 30 minutes, under fixed seating and daytime lighting conditions. This does not capture longer-term occupant adaptation, evolving light patterns across seasons, or movement-based perception (e.g. walking by the window or adjusting shades), which may influence satisfaction over time.

Limited Participant Diversity: The human-subject studies were conducted using a university-based sample, primarily composed of students and early-career adults with high digital literacy and likely prior exposure to VR. The absence of participants from older age groups or non-academic settings may limit generalizability to broader office populations or residential users.

Simplified View and Sky Context: The window views in the IVR environment showed a static outdoor urban context under diffuse sky conditions, with no direct sunlight or dynamic weather effects. In addition, the tested configurations presented relatively low privacy concerns compared to real-world scenarios where occupants might be exposed to overlooking or direct visibility. These simplifications reduced the potential for glare or strong privacy-related responses, which likely explains why clarity emerged as a stronger driver of satisfaction than visual shielding. As such, the conclusions of this study should be interpreted as applicable specifically to diffuse-sky, low-privacy contexts, rather than generalized to all environmental

conditions. Future research should extend testing to scenarios with direct sunlight, variable weather, and higher privacy demands to better capture the full spectrum of occupant experiences.

6.5 Recommendations for Future Research

The results of this study suggest several promising directions for expanding the application of immersive evaluation methods and improving the accuracy of occupant-centered BIPV design.

Conduct Parallel Studies Using Physical Prototypes: Future work should include side-by-side comparisons of real mockups and VR simulations using identical glazing parameters. This would allow researchers to quantify perceptual deviation between virtual and real experiences, and calibrate rendering pipelines accordingly.

Extend Exposure Time and Include Dynamic Interactions: Studies should simulate longer-term use of spaces, including tasks like working, standing, or walking through rooms with BIPV façades. Incorporating changes in outdoor views (e.g. passing traffic, weather, sky brightness) could help reveal how dynamic content affects satisfaction over time.

Expand Demographic and Cultural Scope: Future participant groups should include a wider range of ages, cultural backgrounds, and building types, particularly from sectors where privacy, visibility, or glare sensitivity may differ, such as education, healthcare, or residential housing.

Couple Visual Simulation with Physiological Monitoring: Combining IVR with biometric tools such as eye tracking, EEG, or heart rate monitoring would offer deeper insight into unconscious reactions to view obstruction, glare, or light quality, especially in high-stress or task-intensive environments.

Integrate Economic and Lifecycle Assessments: To support real-world adoption, future research should evaluate the lifecycle cost and embodied carbon of different BIPV configurations alongside user satisfaction and energy performance. This would enable more holistic decision-making for developers and policy makers.

Develop Design Guidelines or Toolkits for Practice: The findings of this study can be embedded in visual decision-support tools or plug-ins for architects and engineers working in BIM environments. A parameterized interface that links TVIS, PV output, DA, and user satisfaction would allow façade design to shift from intuition-based to evidence-based workflows.

6.6 Final Reflection

This thesis demonstrates that BIPV window design is not solely a technical or energy optimization challenge, but also a perceptual one.

It should be noted that glare was not evaluated through the immersive VR environment. To ensure visual accuracy, all VR scenes were rendered under diffuse daylighting conditions without direct sun, while glare-related metrics such as DGP and sDG were assessed separately using validated simulation tools like Radiance and Climate Studio.

By combining immersive evaluation with daylight performance simulations, the research establishes a replicable method to quantify how users experience solar-integrated façades in terms of clarity, privacy, and visual comfort. The findings do not advocate for maximizing energy yield at the expense of occupant experience, nor do they treat visual comfort as secondary to technical performance. Instead, they support an evidence-based balance, where view quality, daylight autonomy, glare mitigation, and energy production are addressed simultaneously as co-equal design priorities.

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APPENDICES

Appendix A: Summary of existing studies of BIPV Windows

Table 22. Summary of existing studies of BIPV Windows

Reference	Year	Research Methods	Solar Cell Type	Research Variables	Building/ Space Type	Key Findings or Gap they referred
Chow et al. [41]	2007	Energy Simulation	a-Si	Thermal Loads Daylight Utilization Electricity Generation	Office	The optimal solar cell transmittance for maximizing energy savings in an office environment was within the range of 0.45–0.55. This configuration provided a balanced benefit in reducing air-conditioning load and maximizing daylight utilization and electricity savings.
Yoon et al. [47]	2013	Field Study	a-Si	Surface Temperature of BIPV windows Inclination angles (0°, 30°, and 90°)	NA	The surface temperature of windows installed on the vertical plane rises significantly during the winter

						season, and on horizontal and inclined planes during the summer due to high solar altitude. BIPV windows had a lower SHGC compared to normal windows, which affects indoor thermal comfort and the building's heating and cooling load.
Markvart et al. [31]	2012	Field Study and Human Subject	Transparent thin-film PV	Solar Cell's Patterns Solar Cell's TVIS Solar Cell's Geometries Visual Comfort Daylight Perception	Office	Preference for horizontal striped patterns over square patterns due to better view quality and lower visual disturbance. MicroShade technology showed positive effects in light environment control.
Lu and Law [119]	2013	Daylighting and Energy Simulation	Semi-transparent PV	Total Heat Gain Output Power Daylight Illuminance	Office	The optimal orientation for BIPV systems to maximize energy performance in terms of electricity benefits was southeast facing. The study found

						significant reductions in cooling loads and electricity requirements for lighting due to improved thermal and power performance of the BIPV systems compared to conventional clear glass.
Ng and Mithraratne [46]	2014	Energy Simulation	a-Si and micromorph-Si	Energy and Carbon Emissions Cost Considerations Developed performance indicators (EPBT (energy payback time) and EROEI (energy returned on energy invested))	Office	The study concluded that commercially available semi-transparent BIPV modules can achieve lower costs than conventional windows with government subsidies, selected modules showed favorable payback periods between 1.1 and 13.1 years.
An et al. [42]	2014	Energy Simulation	a-Si	Types of Windows (clear glass double-layer, heat-absorbing glass double-layer, and Low-E glass double-layer)	Office	The finding was an 18.2% reduction in heating and cooling loads when using the BIPV window model compared to the clear glass double-layer

				Building Operation Times Temperature Settings Air Infiltration from Entrances Internal Loads		window under baseline conditions.
Chae et al. [120]	2014	Lab Study and Energy Simulation	a-Si	Solar Transmittance (0.409 (PV1) to 0.114 (PV3)) Visible light Transmittance (0.301 (PV1) to 0.06 (PV3))	Office	The study found that the properties of the solar cells significantly affect the thermal-optical performance of BIPV windows, indicating the need to customize these properties based on the building's climate conditions to maximize energy performance.
Peng et al. [45]	2015	Field Study	c-Si	Solar Cell Configuration Shading Patterns PV Laminate Temperature Environmental Factors (solar irradiation and temperature)	Office	The study found that the BIPV insulated glass unit (IGU) had a solar SHGC as low as 0.25, much lower than that of commonly used glazing windows. It also highlighted the importance of orientation in maximizing power

						generation, with south and southwest orientations found to be most effective in Berkeley, California.
Kapsis et al. [13]	2015	Daylight Simulation	Si-based (mono-Si and poly-Si) Opaque spaced cells Thin films (a-Si / μc-Si)	Continuous Daylight Autonomy (cDA) spatial Daylight Autonomy (sDA) Daylight Glare Probability (DGP)	Commercial	A semi-transparent PV module with a visible effective transmittance of 30%, integrated as the outer glass layer of a double-glazed window, provides adequate daylight within the perimeter office zone throughout the year, with optimal daylight autonomy and acceptable glare levels.
Do et al. [43]	2017	Energy Simulation	NA	WWR Orientation of Windows (east, west, south, north facing)	Residential	BIPV windows showed significant potential for energy savings, reducing annual energy use by about 12–21%, and peak cooling demand by about 14–26% compared to the

						code-compliant base-case model.
Cannavale et al. [29]	2017	Energy Simulation	PSC	Energy Performance Visual Comfort: (UDI, DGP, spectral quality of light)	Office	The BIPV using perovskite-based glazings could produce significant energy and improve visual comfort, effectively acting as solar control films while generating electricity.
Cannavale et al. [49]	2017	Energy Simulation and Field Study	PSC	Energy Performance Visual Comfort (UDI and DGP)	Office	Perovskite-based PV windows not only significantly reduce the occurrence of high DGP but also improve UDI compared to conventional clear glass. These windows could potentially exceed the electric energy used for artificial lighting.
Sun et al . [121]	2018	Energy Simulation	CdTe	WWR PV Glazing Coverage Ratio PV Glazing Placement Climate Conditions	Office	Integration of BIPV windows with large WWR and a significant portion covered by PV glazing, while maintaining sufficient daylighting area,

						showed the lowest net energy consumption and improved daylight performance, especially under specific climate conditions.
Joseph et al. [122]	2019	Field Study	Monocrystalline silicon semi-transparent PV	Solar Irradiance Air Temperature Relative Humidity Wind Speed Module Temperature	Office	The performance of the BIPV systems decreases with increasing module temperature despite higher irradiance. The study observed that the semi-transparent window glazing provided indoor environmental visual comfort with energy savings of between 11% and 19%.
Alrashidi et al. [123]	2020	Field Study	CdTe	Thermal Transmission SHGC U-value	NA	The semitransparent CdTe BIPV window had significantly lower solar heat gain compared to traditional single glazing, with a SHGC of about 20%, thereby reducing cooling

						loads and enhancing energy efficiency in building applications.
Mesloub et al . [44]	2020	Energy Simulation	a-Si	daylight autonomy (DA) UDI DGP	Office	The integration of BIPV windows with internal light shelves did not meet the visual comfort requirements using a-Si modules due to low transmittance. Still, it achieved significant energy savings, especially on the east-west axis.
Mesloub et al. [124]	2020	Energy Simulation and Field Study	a-Si micromorph	PV Module Types WWR TVIS Cardinal Orientations Tilt Angles	Office	The study found that the optimum BIPV window design under a semi-arid climate could lead to maximum energy savings of 60% with double-glazing PV modules towards the south orientation. It also significantly minimized the glare index compared to the base model.
Chung et al. [50]	2020	Energy Simulation	DSSCs	TVIS PCE	Office	The study predicted that DSSC windows

				U-value SHGC Solar Coefficient (SC)		with 13% PCE and 30% TVIS could achieve significant energy savings (4861.44 kWh/yr), and that windows with over 50% TVIS at any PCE would be beneficial for net zero-energy and net energy-plus buildings.
Chen et al. [51]	2021	Energy Simulation	a-Si	WWR Urban Canyon Aspect Ratio Urban Canyon Orientation Window Coverage Percentage	Urban office buildings	The study found that BIPV windows reduce building cooling load and canyon air temperatures compared to clear glass windows. Savings on cooling energy consumption vary between 9.16% and 63.71%, with the benefits increasing in open street canyons and large window-to-wall ratios.
Ghosh et al. [48]	2021	Daylighting Simulation	PSC	DGP Correlated Color Temperature (CCT) Color Rendering Index (CRI)	Office	The study found that a visual transmittance range of 50-70% was optimal for maintaining

						comfortable daylight conditions in south-facing vertical plane BPV windows in hot desert climates. However, high transmittance levels due to increased glare made high visual comfort challenging to achieve.
Kishore et al. [34]	2022	Computational Simulation	DSSC	WWR (40%, 60%, 80%) Type of Glazing (double and triple-glazed windows with inert gas and DSSC) Climatic Zones (temperate, humid subtropical, continental, temperate/mediterranean, tropical monsoon, and dry arid climates).	Commercial	Triple-glazed windows with DSSC were the most efficient solution for improving energy performance, particularly in smaller buildings.
Chen et al. [125]	2022	Energy Simulation	a-Si	Canyon Aspect Ratio Window Coverage Power Generation Efficiency Canyon Air Temperature	Urban office buildings	The study identified that canyon aspect ratio, window coverage, and power generation efficiency are pivotal for

				Building Cooling Load Momentum Roughness Length above Canyon Thickness of Building Envelope Air Conditioning Setpoint Temperature		maximizing electricity generation from BIPV windows, which have strong dynamic interactions with the building's indoor space and surrounding urban canyon environment.
Chen et al . [126]	2024	Energy Simulation	a-Si	Canyon Aspect Ratio Window Facing Orientation WWR	Urban office buildings	Compared to clear windows, BIPV windows can achieve considerable energy savings for office buildings with large window coverage and high solar access. However, they can increase energy consumption when window coverage is small.

Appendix B: Summary of Existing Studies on Window View Assessments

Table 23. Summary of existing studies of Window view Assessments

Reference	Year	Study Objective	Research Methods	Metrics evaluated	Window / View Variables Studied	Environment Type	Number of Human Subjects	Window Type and Material	Key Findings
Finnegan & Solomon [127]	1981	Assessed the impact of having or not having a Window in the workplace and related work attitudes	-Quantitative survey -Comparative analysis (t-tests)	-Job satisfaction -Interest value -Time sense -Sense of space -Anxiety -Physical working conditions	Presence vs. absence of windows.	Real-world office	123	NA	Occupants in windowless offices were significantly less satisfied with job satisfaction, interest value, and physical working conditions. While no significant difference in anxiety, time sense, or spatial perception was reported.
Ulrich [60]	1984	Assessed the impact of exposure to a window view of nature (greenies) vs. a built wall influence the surgery recovery.	-Over 9 years of patient records -Wilcoxon signed-rank tests, Hotelling multivariate tests	- Length of hospital stay - Nurse note tone (positive/negative) - Quantity and strength of analgesic and anti-anxiety medication -Minor postsurgical complications	View content (tree vs. wall)	Hospital patient rooms (2nd and 3rd floors)	46	A Rectangular window (1.83 m × 1.22 m)	Patients with a nature view had: - Shorter stays (7.96 vs. 8.70 days) - Fewer negative nurse notes (1.13 vs. 3.96 per patient) - Less use of strong/moderate pain meds on days 2–

									5 - Slightly fewer minor complications
Verderber & Reuman [128]	1987	Assessed the impact of various person–window relationships on the well-being of hospital staff and the health status of inpatients in rehabilitation units.	-Behavioural observation over 7 days -Staff questionnaires -Patient health status ratings -Environmental audits -Multivariate regression analysis	Staff: -Job satisfaction -Perceived care quality -Well-being Patients: -Composite health status index based on 19 indicators (e.g., emotional outlook, social interest, prognosis, physical condition).	-Proximity to window -View content -Screen use -Window-to-wall Ratio -Sill height -Daylight exposure.	PMR units in 6 hospitals: (patient rooms, staff offices, and therapy rooms)	137 Hospital Staff 100 Patient	NA	-Patients had poorer health status in windowless spaces, or had obstructed views, high sills, or were far from beds. -View quality, sill height, and proximity were strong predictors of health. -Staff were also affected, especially those in windowless offices. -The study supports that window design affects both therapeutic recovery and workplace well-being.
Kaplan [129]	2001	To assess how residential window view content affects well-being and satisfaction.	-Survey (verbal + photo-based) -Factor Analysis -Regression Model	-Residential satisfaction -Well-being (effective, calm, distracted) -View content/preference.	View Content: -Trees -Gardens -Parked cars -Streets -Buildings -Weather	6 low-rise apartment communities	188	Standard apartment windows.	-Natural view: increase satisfaction -Built views: decrease satisfaction -Preferred views are the best predictor.

Dogrusoy, I. T., & Tureyen, M.[33]	2007	Identified office workers' preferences for window types and the sub-factors influencing these preferences.	- Field study (6 buildings in İzmir) - Survey using 3D-rendered window-type images - One-Way ANOVA	- 16 sub-needs (e.g., daylight, ventilation, spaciousness) - View quality - Task type (mobility, creativity) - Gender	- Window shape (square, horizontal, vertical, round, window-wall) - Window-to-wall ratio (22%, 44%, 100%) - View quality (rated: high, average, poor)	Office	221	-7 types of simulated windows -Clear glazing	- Window-wall and horizontal windows most preferred. - Top needs: daylight, ventilation, spaciousness. - View content less important than having visual contact. - Preferences varied by gender, creativity level, and view quality.
Arie et al. [59]	2010	To model how view type, view quality, window distance, and social density affect discomfort, sleep, and lighting satisfaction in offices.	- Field survey - Path analysis (structural equation modeling) - Site visits and workstation observations in 10 office buildings	- Sleep quality - Environmental utility (glare/heat) - Light quality - Office impression	- View Type (urban / nature) - View Quality (bad / neutral / good) - Window Distance (0–2 m, 2–4 m, >4 m) - Social Density (1–2, 3–5, >5 people)	Office	333	Clear Window	- Better view quality reduces discomfort. - Nature views improved impression but also increased discomfort slightly. - Sitting farther from the windows reduced glare and heat issues. - Less discomfort was linked to better sleep.
Yun et al. [86]	2011	To examine how different types of window views affect	- Lab experiment with a simulated window - Subjects rated	Discomfort Glare Scale (Hopkinson)	- View content (blank, natural land, natural	Controlled lab space (6.25 × 4.55 × 2.5 m)	48	Clear Window	- Most views reduced glare vs. blank condition. - Distant man-made

		subjective evaluation of discomfort glare.	glare from 11 different views at 5 luminance levels - Statistical tests (ANOVA, ANCOVA, t-tests)		river, man-made, mixed land, mixed river) - View distance: far (three-layer image with sky), near (two-layer image without sky) - Luminance (1000–10,000 cd/m^2)				view had lowest glare scores. - Some natural views increased glare slightly. - Clear differences between glare-sensitive and glare-insensitive users.
Hellinga & Hordijk [69]	2014	To create a method that measures both daylight access and view quality in a single analysis.	- Development of D&V method - Projection via hand drawings, 3D software (Radiance), or a fisheye camera - Comparison of View Quality Scores with mean participant ratings	-Daylight Access View Quality: - Character of the view - Natural green - Layers visible - Natural water - Nearby traffic - Diversity - Buildings in the view (Maintenance, Features) Visual Comfort: - Luminance distribution	-Glazing orientation and position - Elements in view: water, green, buildings, traffic - Projection methods (photo/render/sketch)	Office	484	Clear Window	-The D&V method assesses daylight and view quality simultaneously. -View Quality Scores (0–12 pts) showed strong correlation with user ratings. -Useful for early-stage design to evaluate both daylight and outside views.
Konstantzos et al. [70]	2015	To develop a metric (VCI) for evaluating view	Field Experiment - Real-scale office setup	VCI -shade openness factor	-Viewing Distance (1 m and 2.4 m)	Office	18	High-performance glazing unit with	Darker fabrics with higher openness achieved higher view

		clarity through different shading fabrics.	- 14 roller shades - 2 viewing distances (1 m, 2.4 m) - Sunny and cloudy conditions - Subjective + objective testing - Statistical analysis (ANOVA, t-test)	-visible light transmittance -view layer visibility -color visibility -visual acuity	-Varied types of shading fabrics (1%–13% openness, 3%–25% T_v) -Sky condition (sunny/cloudy)			a Low-E coating with varied types of shading fabrics.	clarity scores, and a View Clarity Index was developed, incorporating shade openness factor and visible light transmittance. VCI = 1.43 × $(OF)^{0.48}$ + 0.64 × $(\frac{OF}{T_v})^{1.1}$ - 0.22
Matusiak & Klöckner [83]	2016	To examine how qualitative and quantitative parameters of a window view impact perceived view quality in real workplaces.	-Field Experiment - Interviews + photo documentation - Ordinal logistic regression	**Perceived view quality** (4-point scale) **Quantitative Variables:** (view depth view width number of view layers fragmentation greenery individual differences (gender, age) **Qualitative Variables:** aesthetical quality composition	- View distance (max, min) - Number of visual layers - Aesthetic quality of scene - Greenery presence - View composition - Fragmentation (mullions/obstructions)	Office	106	Clear Window	- Best predictors of view quality: distance, layers, and aesthetic quality of the scene. - Greenery and view width not significant when other variables included. - Composition strongly correlated with aesthetic quality. - No formula introduced; findings inform future view quality standards.
Konstantzos &	2017	To evaluate visual comfort, energy use, and	Energy Simulation and Daylighting simulation	**-Visual Comfort Autonomy** (VCA) **-Daylight**	**Shading Controls** (fully open, fully	Office	NA	Double-glazing windows with interior roller	For south-facing offices, advanced shading controls and

Tzempelikos [72]		outdoor view in private offices using a triple-metric framework.		**Autonomy** (cDA) **-Connection to the Outdoors** (EOV) **-Seating Layout** (facing the window, facing the side wall, and facing away from the window) **-Orientation** (south-facing, north-facing)	closed, standard shading control, advanced control) **VCI** **Solid Angle** (portion of the occupant's visual field covered by the window)			shades (OF = 4.2%, T_v = 5%)	a layout facing the window were found to balance comfort, lighting energy performance, and connection to the outdoors. North-facing offices could achieve acceptable conditions without shading. EOV = $\frac{1}{\Omega_{FOV}} \sum_i VCI_i . A_i . \frac{1-\cos\theta_i}{2}$ $\sum_i VCI_i$: Is the View Clarity Index for each window fragment, A_i: Is the area of each visible window fragment, θ_i: is the angle between the normal to the window and the line connecting the eye and the fragment, Ω_{FOV}: The overall solid angle of the human visual field is approximated as a

									circular cone with a half-angle of 78 degrees.
Zanon et al. [78]	2019	To develop a comprehensive Visual Quality Index (VQI) for residential buildings integrating daylight, glare, color temperature, and qualitative aspects.	Simulation study using Rhino + Grasshopper + Honeybee + Dialux	**Quantitative Metrics:** - sDA - sDGP - Em (maintained illuminance) - UGR (electric glare) - CCT (color temperature) **Qualitative Checks:** - View out - Shading control - Dimming - Lighting integration	View Content: -Nature (flora, fauna, sky) -Dynamic features (movement) View Access: -Content distance (≥ 7.5 m) Design Inputs: - Window orientation - Glazing transmittance (TVIS = 71%) - Shading type and control - Eye-level viewpoints & room layout	Residential	0	Double-glazed windows (TVIS= 0.71, transmittance = 0.5)	The study successfully developed a visual quality index that proved useful during the design process of residential buildings, facilitating improvements in electric illumination and daylight access. VQI = $100 \cdot f_I + 70 \cdot f_{II} + 35 \cdot f_{III} + 0 \cdot f_{IV}$
Turan et al. [65]	2019	To develop a framework for evaluating spatially distributed views throughout	Simulation study using Rhinoceros 3D, Grasshopper	- View object types (sky, ground, vegetation, landmarks) - View diversity - Depth-of-field	- Internal partitions -External shading devices -Façade elements	Office	0	Clear Window	- Proposed a dynamic, position-sensitive method to map view metrics across a space. - No quality score; designers interpret

		open-plan workspaces.							weighted view maps.
Mardaljevic [75]	2019	To introduce a new quantitative metric, “View Lumen,” for evaluating view potential at the aperture level using daylight-based modeling.	Radiance Simulation	- View Lumen (lm) for Different Components of View (sky, natural/man-made objects, ground) - Total aperture view loss (φ_{lost}) - Aperture Skylight Index (ASI) - Integration with Sunlight Beam Index (SBI)	- Aperture reveal geometry (depth, position) - Layered zones: sky (top), obstructions (middle), ground (bottom) - Self-luminous surroundings	Generic building façade and window configurations	0	Clear Window	The study found the introduction and preliminary validation of the 'view lumen', which provides a quantifiable measure of view at the building aperture and potentially serves as a regulatory tool for evaluating daylight and view in building design. φ_{lost} =2000A−(φ_{sky}+φ_{obs} +φ_{gnd})
Li & Samuelson [130]	2020	To propose a new method for view visualization and evaluation.	Building Simulation with Rhino	- View Score (weighted area of desirable, neutral, and undesirable views) - View range (horizontal & vertical FOV from multiple positions) - Efficiency comparison with	- Window geometry (size, height, position) - Room dimensions (depth, height) - Occupant viewpoint (front, middle, back) - Panoramic views (360° images)	Office	0	Clear Window	-Introduced **View Score** metric: weighted evaluation of views based on user-defined preferences (e.g., landmark, greenery, clutter) over panoramic images. -Presented **FOV-based equations** to model visual range.

				traditional modeling	- Obstructions and shading depth (L1, L2)				- Method was 88% faster than traditional 3D modeling for view assessment.
Kent & Schiavon [79]	2020	To evaluate how the distance of view content in window views affects satisfaction, and whether that effect differs between nature and urban elements.	- Online survey (image-based rating) - Controlled experiment using an artificial window - Statistical tests: t-tests, Wilcoxon, MANOVA	**Visual Satisfaction** Connection to the outside View content View privacy **OLD (Observer Landscape Distance)** from near (<6 m) to distant (up to 851 m)	- View content: Urban vs. Nature - Horizontal stratification (sky, landscape, ground) - Number of visible layers	NA	141: 91 (survey) + 50 (lab)	Clear Window	Participants preferred distant views for urban features and closer views for natural features to achieve visual satisfaction.
Abd-AlHamid et al.[87]	2020	To assess how viewing location (close, middle, far) impacts perceived window view quality and stress recovery using immersive VR.	Virtual Reality and Human Subject	-View Restorative Ability -View Content -View Size -View Valance/Arousal -Self-reported Stress PANAS Positive and Negative Affects -Skin Conductance level (SCL) -Heart Rate (HR), HRV (LF, HF)	- Viewing location: close (0.87 m), middle (2.18 m), far (3.55 m) - View content: urban + nature elements - Sky visibility varied by location	Office	32	Double-glazed clear window, 20% WWR, 1:1 aspect ratio (1.4 m × 1.4 m)	The study found significant differences in subjective view perception parameters across different viewing locations, indicating that closer proximity to the window enhances perceived view quality and restrictiveness.

Ko et al. [62]	2021	Proposed a comprehensive framework to assess window view quality	Framework development	**View Quality Index (VQI): - View Content** (layers, distance, nature, dynamic features) **- View Access** (view angle, spatial coverage) **- View Clarity** (clarity index, obstructions, material effects)	-View Content: Nature, movement, distance, horizontal layers -View Access: View angle, distance, spatial area -View Clarity: Glazing/shading type, clarity index, visual parallax	-	0	-	Introduced the **View Quality Index (VQI)** = *Vcontent* × *Vaccess* × *Vclarity*. Includes equations for each component and thresholds (0–1 scale) to categorize view quality as Insufficient, Sufficient, Good, or Excellent. Clear framework for integrating view quality into design practice. Emphasizes need for more empirical validation and incorporation into green building standards.
Garretón et al. [131]	2021	To evaluate nine roller blind fabrics under real daylight conditions and propose a selection protocol based	- Field Experiment in real daylight lab	**- Discomfort Glare Probability (DGP):** GP score **- View Clarity Index (VCI):** VO score **- Useful Daylight Illuminance (UDI):**	- Fabric type (9 types) - Openness Factor (OF) and Visible light Transmittance (TVIS) - Internal position near	Simulating office	0	6 mm single clear glazing (TVIS = 88%) with mounted roller blinds made of polyester/fiberglass coated	-Introduced a comfort-based selection method comparing glare, view clarity, and daylight using three independent and weighted scoring systems.

		on comfort performance.		DA score **- Composite fabric score via ternary weighting**	window - Solar position (sun in field of view)			with PVC; 1.0 m × 1.0 m window	-Used and validated **VCI** equation: VCI = (1.43 × $(OF)^{0.48}$ + 0.64 × $(\frac{OF}{T_v})^{1.1}$ - 0.22)/100
Flor et al. [84]	2021	To assess user acceptance of different ETFE cushion types in double-skin façades using immersive VR, focusing on view clarity and emotional response.	-Virtual Reality - Statistical analysis (Friedman, Wilcoxon tests)	**View Clarity** (clear, fritted, and switchable) **- Satisfaction** **- View amount** **- Appearance, perception, vividness** **- Emotional response: spatial pleasure, arousal, dominance**	- Glazing configuration (clear DG, + clear ETFE, + fritted ETFE, + switchable ETFE) - Print density (71–74%) - Cushion position (300 mm from DG) - Obstruction type and pattern (fritted or switchable)	Office	22	14 mm double glazing (clear) with 3 ETFE DSF variants: • DSF1: +Clear ETFE • DSF2: +Fritted ETFE (71%) • DSF3: +Switchable ETFE (74% double fritted foil)	-Double glazing (REF) rated highest in all view clarity and emotional categories. -Switchable ETFE (DSF3) ranked lowest due to obstruction. -Clear ETFE (DSF1) preferred over fritted (DSF2) and switchable ETFE in view quality. -DSF3 significantly reduced satisfaction, clarity, and dominance (r > 0.6). -Findings highlight need for better frit designs for acceptable view quality in adaptive façades .

Flament et al. [71]	2022	To assess view clarity through nine solar shading fabrics under real daylight and revise the View Clarity Index (VCI) model.	- Field experiment - Questionnaire	- Normalized view clarity scores (0–1) - Luminance at eye level (Ev,eye) - Fabric luminance (L) (interior and exterior vertical and horizontal) - View Clarity Index (original and revised)	- Fabric type: Color: (white, grey-white, black-grey) and OF: (1%, 3%, 10%) - Light Transmission (τ_v) -Light Reflectance (ρ_v) - Fabric brightness and solar exposure	Real-world outdoor test cells (Controlled Lab)	50	Double-glazed vertical window (τ_v= 82%) + 9 external roller shades (vinyl-coated fiberglass, OF = 1–10%)	The study observed that view clarity is highly influenced by the fabric's OF and colour. Based on these observations, a revised formula for the VCI was proposed. VCI=$-0.461\times e^{-66.6\times\tau_{v,n-n}} -0.467\times\frac{(\tau_{v,n-dif})^{0.296}}{(\tau_{v,n-n})^{0.222}} +0.921$ $\tau_{v,n-n}$ represents the normal-normal light transmittance factor. $\tau_{v,n-dif}$ is the normal-diffuse light transmittance factor
Ko et al. [132]	2022	To define window view quality through expert consensus and outline research priorities and integration strategies in design tools,	Position statement developed through expert workshop (UC Berkeley, Oct 2021) and literature synthesis; endorsed by 54 researchers from academia, practice, and policy.	Introduced a conceptual framework with three components: -View Content -View Access -View Clarity	- Content: natural vs. manmade, layers, movement, distance - Access: viewing angle, position, spatial availability - Clarity: glazing,	-	-	-	-Introduced a framework with content, access, and clarity as core components. -Identified major research gaps (e.g., clarity thresholds, satisfaction curves) and called for integrated view

		standards, and certification systems.			shading, reflections, obstructions				metrics in design tools and green standards (LEED, WELL).
Lin et al. [77]	2022	To assess which quantitative and qualitative features of window view content most influence occupant preference ratings.	-Human Subject: Image-based survey using 80 static photos of window views - Statistical tests (ANOVA, Tukey, Pearson)	**Natural feature ratio** (sky and greenery) **Artificial feature ratio** (buildings) **Number of layers** (ground, greenery, buildings, far elements, sky) **Horizontal layers** **Far elements** (>50 m) Cloud level	- View composition: natural vs artificial content - Number of layers - Aesthetic features (composition, distance) - Horizontal stratification and visual balance	Office	445	Clear Window	-Natural elements (sky + greenery + water) showed strongest correlation with preference. -More layers increased view preference; 3–5 layers rated higher. -Far elements (>50 m), horizontal stratification, and composition were positively associated with preference. -Artificial content (e.g., deteriorated buildings, clutter) lowered preference; urban views need careful composition.
Kim et al. [76]	2022	To develop and validate a predictive tool (Seemo) for evaluating window view	Online Survey	- Satisfaction scores (−5 to +5) for: +View Content +View Access +Privacy	- Window Size: Number of windows, sum of window areas - View Composition:	Residential	181	Clear Window	-Developed and validated the Seemo tool with R^2 up to 0.90 for predicting view satisfaction. -Sky ratio, floor

		satisfaction in residential design.		+Overall - 23 ray-cast view variables (e.g., Sky %, Trees %, Equipment %, distance to view elements)	Horizontal window area ratios - View Parameters: Sky, tree, water, building, vegetation, equipment, dynamic feat - Distance to View Objects: Distances to trees, water, buildings, equipment, dynamic elements - Other Parameters: Floor height (FH), view diversity (EN), sky condition (SC: invisible, overcast, clear)				height, and distance to dynamic elements were top predictors. -Seemo outperformed Ko et al.[62] framework in differentiating subtle view quality changes.
Abd-AlHamid et al. [81]	2023	To evaluate how window size and layout affect view quality, stress	Virtual Reality	- View perception (fascination, content, interest, complexity, etc.) - PANAS stress	- Window size (WWR: 10%, 20%, 30%) - Window layout (wide vs narrow)	Office	25	Double-glazing windows	-Larger windows (WWR 30%) enhanced view perception and stress recovery

		recovery, and psychological affect.		indicators - Physiological measures	- Same urban view across all conditions				significantly. -Window layout only affected perception at small size (WWR 10%) — wide performed better than narrow. -WWR alone is not a reliable view quality indicator for small windows. -Physiological data partially supported these findings.
Kent & Schiavon [80]	2023	To assess whether the five "environmental information criteria" used in daylighting standards can predict window view preferences.	Human Subject	- View preference - Environmental criteria (location, time, weather, nature, people) - Psychological restoration - Emotional affect (7 items)	- View type (nature, urban, mixed) - Content distance (2 m to 851 m) - Horizontal layers (ground, landscape, sky) - Nature connectivity, weather, time visibility, movement	NA	451	Clear Window	Findings include that environmental information criteria can predict window view preferences effectively, and as ratings for these criteria increased, so did ratings for psychological restoration and positive affect.
Ko et al. [82]	2023	To quantify how geometric window	Virtual Reality and Human Subject	Satisfaction with the number of	- WWR (10%, 20%, 30%, 40%, 45%, 67%)	Office	40	Clear Window	The study found that glazing area (WWR), window distance,

		variables affect satisfaction with view access, and to propose an empirical view access index (VAI).		views (−3 to +3 Likert scale)	- Horizontal and vertical view angle - Viewing distance (2 m, 5.5 m, 9 m) - Viewing direction (parallel, perpendicular) - PWV: % of window in field of view (visual cone)				and viewing direction are the primary predictors of satisfaction with view access. Based on these variables, it developed a view access index.
Koga et al. [133]	2023	To quantify the effect of visible greenery (green view factor) on window view satisfaction in urban offices.	Simulation Using VR	- View satisfaction score	- Green View Factor (GVF: 0%–100%) - Tree type (low vs tall) - Layout and spacing of greenery - Indoor vs outdoor plants - Observation distance: 5 m	Office	47	Clear Window	- Greenery increased satisfaction by 20–30 points compared to views of only buildings. - Satisfaction was highest for moderate GVF (~25–50%), not at 100%. - Outdoor trees preferred over indoor plants; indoor greenery layout affected spatial perception. - Too much greenery reduced satisfaction

									due to visual overload or perceived enclosure.
Zeng & Zhang [134]	2023	To develop a VR-based window view evaluation for analyzing the combined effects of shading devices and exterior landscapes on user satisfaction.	Simulation Using VR	- Satisfaction with shading, glare, and landscape - Emotional response: pleasant, interesting, exciting - Heart rate difference - User feedback on glare and clarity	- 3 levels of landscape - 6 shading devices - Fixed geometry (WWR 40%) - sDA and sDG daylight metrics - Position fixed at 2 m from window, eye height 1.2 m - Glare zones	Office	30	South-facing clear glass window (2.9 m × 1.6 m)	- Shading types that block less of the view were preferred despite allowing more glare. - Advanced landscape increased satisfaction, lowered heart rate, and improved perception of shading devices. - Significant interaction found between landscape and shading on satisfaction.
Domjan et al. [135]	2023	To compare subjective view quality ratings with physiological responses and propose a refined model for predicting perceived window view quality.	Lab Experiment	- Window View Vote (WVV) - VOQ and VQI-based indices - Gender/age correlations	- View motif (natural vs built) - Presence/absence of sunlight (sunny vs cloudy) - View layer (sky, ground, trees, buildings) - Distance and layering	Office	43	Clear Window	The finding was that window view votes increase with the dominance of natural elements and sunny conditions. Observers' physiological responses were significantly less pronounced than their subjective

					- Static vs dynamic motif features				votes, with frontal alpha asymmetry showing the highest positive response to natural elements and sunny conditions.
Ko et al. [112]	2024	To develop an experimental workflow to assess how different glazing and shade materials impact view clarity, visual performance, and satisfaction.	Lab experiment	- Visual acuity - Contrast sensitivity - Color matching - Color arrangement score - Satisfaction (7-point Likert)	- Material type - TVIS (1–31%) - Solar reflectance (RS) - Fabric openness factor (OF) - Shade color (light, medium, dark grey, black) - View content type (building, pond, street/people)	Controlled Lab	50	Clear Window	- Specular materials (films, EC) yielded better visual performance and satisfaction than fabric shades. - Higher TVIS and lower RS (darker shade color) improved clarity and satisfaction, especially for fabric shades. - Color (not just OF) strongly influenced performance, dark grey fabric outperformed medium grey even at same TVIS. - Visual acuity and color matching were the best predictors of view satisfaction.

Wang & Munakata [104]	2024	To analyze how window-to-wall ratio (WWR), height-to-width ratio (HWR), and floor level affect perceived oppressiveness in high-rise views.	Simulation Using VR	- Perceived Oppressiveness (PO) - Sky Ratio (SR) - Building Ratio (BR) - Greenery Ratio (GR) - Environmental Preference (EP)	-WWR (25%, 50%, 75%) - HWR (1:2, 1:1, 2:1) - Floor Level (2F, 10F, 18F) - Sky, Building, and Greenery visual ratios (SR, BR, GR) - Viewer distance and height fixed at 0.5 m and 1.5 m	NA	40	Clear Window	- Higher WWR reduced oppressiveness, while higher HWR increased it. - PO was highest on 10F (moderate sky + high building ratio), lowest on 18F (high sky, low building). - Sky ratio (SR) significantly decreased PO; building ratio (BR) increased PO.
Khanei & Andersen [89]	2024	To investigate how solar shading systems affect the subjective perception of view through photometric compositions.	Human Subject Field Experiment	-View assessment -View satisfaction - Local contrast (LC) -Global contrast (GC) -RMS (complexity) -Bright spots -Glare Index (GI) -DGP	-Slat direction (horizontal/vertical) - Slat type - View distance (1, 2.25, 3.7 m) - Slat angle (0°, 5°, 10°, 25°, 35°) - Interruption frequency (few/many) - VQR of each view position - Angular access	Office/Meeting Room	64	Clear Window	-Bright spots reduced perceived view quality. -Local contrast improved clarity but lowered satisfaction. -Horizontal slats were preferred over vertical ones. -Fewer visual interruptions improved both clarity and satisfaction.

					to greenery, sky, obstruction				
Kent et al. [136]	2024	To review how different types of window shades (fabric, solid, glazing) impact view clarity.	Literature review	-Shading Solution -View Content -Observer	- View Clarity	-	-	-	- View clarity is shaped by interactions among shade type, view content, and the observer. - Fabric shades reduce clarity for natural views and can create glare -Solid shades that align with view layers often fracture or obscure the view. -Glazing solutions preserve clarity better but may distort colors or reflect interiors. -Shade design must consider view composition, user needs, and spatial layout.
Sheng et al. [90]	2024	To examine how different bird collision prevention	VR experiment	- View clarity - Effect of pattern type, coverage, and spacing	- 3 marker types: dot, horizontal stripe, vertical	Office	60	Clear Glass with dot/stripe pattern	- Horizontal and vertical stripes provided higher clarity than dots.

		glazing patterns affect occupants' perception of window view clarity.			stripe - Coverage rates: 3%, 5%, 10% - Spacing: small vs large - Scene height (3rd and 10th floor)				- Higher coverage rates significantly reduced clarity (10% lowest scores). - Larger spacing improved perceived clarity for stripes; small spacing better for dots. - Most participants were willing to slightly sacrifice view clarity to prevent bird collisions. - Recommends balancing pattern type, spacing, and coverage in design for both view and bird safety.
Wasilewski & Andersen [74]	2024	To propose a method for quantifying view visibility through various façade systems using a visual difference prediction model (HDR-VDP-3).	- Simulation-based study using HDR-VDP-3	- View Visibility (% retained contrast) - Pixel-wise HDR contrast maps - Comparison to geometric openness ratios	- Façade system type (glazing, fabric shade, venetian blind) - TVIS, RVIS, openness factor (OF) - Slat angle (0°–45°) - View content type (trees,	-	-	Clear glass (80% TVIS), EC glazing (1%, 6%), fabric shades (light/dark, 4–8% OF), venetian blinds (varied tilt angles)	- HDR-VDP-3 effectively estimated view degradation due to pattern masking, veiling, and reflection. - View visibility was highest for clear glazing, lowest for 1% EC and light fabric under strong

					buildings, sky) - Daylight vs electric lighting - Veiling reflections and pattern masking effects considered				sunlight. - Fabric shades outperformed their geometric openness; venetian blinds underperformed due to masking. - View content mattered: scenes with horizontal edges (buildings) were more obscured by horizontal blinds.

Appendix C: Summary of existing studies of IEQ using VR

Table 24. Summary of existing studies of IEQ using VR

Reference	Year	Type	Human Subject	Aim of the study	IVR Validation	Validation Method	Measures	Key Findings
Kort et al. [110]	2003	Filed Experiment and IVE	101	To explore the comparability of research findings in real and virtual environments and to assess the potential of virtual environments as research tools for environmental psychology.	Yes	Statistical Analyses ANOVA Factor Analysis	Cognitive mapping Height estimations Environmental evaluations Perceived functions afforded by the environment	The study found differences between real and virtual environments in terms of performance measures and evaluative measures. However, responses to a subtle environmental change (presence of plants) were generally similar in both environments, indicating that virtual environments can serve as valid research tools, but further exploration is necessary.
Westerdahl et al. [137]	2006	VR	99	The study aimed to investigate the usability of a VR model of a building in the context of architectural planning and how well it matched the experience of the actual building.	Yes	Survey Responses Semantic Environment Description Scale	Environmental Description Scale (SMB): (Pleasantness, Unity, Complexity, Enclosed Ness, Participants' ability to Make Decisions, Orientate, and Evaluate Realism.)	The study found that the VR model provided a fairly accurate representation of the real building, and participants felt it was useful in making decisions about their future workplace.

Saeidi et al. [138]	2015	Lab Experiment (in-situ) and VR	10	Determine a procedure or methodology for validating the effectiveness of IVE applications for studying occupant behavior and enhancing IVE research designs for measuring occupants' energy behaviours.	Yes	**Visual Perception Questionnaire** **Assessing 5 types of validity** (ecological, internal, construct, and criterion validity) **Comparative Analysis**	**Ecological validity** (sense of presence) **Internal validity** (cause and effect relations) **Construct validity** (Visual comfort, stimulation, and mood) **Criterion validity** (behavioural predictions) External validity	IVE can replicate real-world field experiments effectively, making it a promising method to improve building energy simulation models. However, the study acknowledges its limitations and suggests further research with larger sample sizes and improved equipment.
Heydarian et al. [94]	2015	Field experiment and IVE	112	The study investigated whether IVEs adequately represent physical environments for building design and user-built environment explorations. It compared user performance in everyday office-related tasks between the two environments.	Yes	**Survey Responses** **Physical Measurements** **Statistical Analysis** (t-test) **Behavioral Observations**	**Lighting conditions** (dark and bright) **Types of tasks** (reading and object identification) **The environment** (IVE versus physical)	The study concluded that participants performed similarly in an IVE setting compared to a physical environment for all measured tasks. Additionally, it demonstrated that IVEs can be an effective tool during the design phase of Architecture, Engineering, and Construction (AEC) projects to acquire end-user feedback, potentially leading to better infrastructure design and satisfaction.
Heydarian et al. [100]	2015	IVE	15	The study aimed to understand end-	No	-	**User lighting performance** (Lux)	The study found that IVE can effectively collect data on human preferences and

				users lighting preferences and collect performance data within office spaces. It used immersive virtual environments to inform better building designs that increase user satisfaction and potentially reduce energy consumption.			**User performance** (Reading speed &comprehension	performance, which can then be used to create profiles for end-users. These profiles can help design environments tailored to user needs, leading to higher satisfaction and reduced energy consumption.
Heydarian et al. [139]	2017	VR	89	The study aimed to collect end-user lighting-related behaviour using IVEs, translate this data into quantitative measures using BPS tools, and incorporate user preference data to evaluate design alternatives, aiming to balance end-user lighting preferences and energy efficiency.	No	-	**Lighting preferences** **Personality traits, and their impact on performance** **User satisfaction**	Participants preferred simulated daylighting over electric lighting and performed better in environments with maximum simulated daylighting. Furthermore, personality traits influenced lighting preferences, with extroverts tending to prefer maximum lighting. The study also demonstrated how user preferences could guide building design, improving energy efficiency and occupant satisfaction.
Chen et al. [95]	2018	Field experiment & VR & Video, &	40	The study aims to evaluate the feasibility of using alternative media,	Yes	**Survey Responses**	**Presentation modes** (VR, video, photo, and real space)	The study found that VR reproductions are rated closer to physical environments than video and photographic reproductions. VR also provides a better representation of

		Photographic reproductions		including VR, video, and photographic reproductions, to present physical lighting environments and compare these media's presentation ability to actual physical environments.		**Physical Measurements** **Correlation Analyses**	**Lighting scenes** (Different colour temperatures) **Six presentation factors** (sense of presence, realism, field depth, stereo, comfort, and clarity)	lighting attributes such as open/close, diffuse/glaring, and others, leading to higher participant satisfaction.
Saeidi et al. [140]	2018	Lab Experiment (in-situ) and IVE	1	The study aims to validate the use of IVEs for occupant behaviour studies, mainly to generate longitudinal data for predictive modelling related to building energy consumption.	Yes	**Physical Measurements** **Spatial-Temporal Event-Driven (STED)** **Fisher's exact test**	**States** (Non-occupancy without artificial lighting, Non-occupancy with artificial lighting, Occupancy without artificial lighting, Occupancy with artificial lighting) **Events** (Arrival at the office, Intermediate (short) leave, Return from intermediate short leave, Intermediate (long) leave, Return from intermediate	The study finds that IVEs can produce comparable occupant behaviour patterns to in-situ studies, particularly in capturing state transitions across events. This validates their potential for longitudinal occupant behaviour studies and predictive modelling.

							long leave, Departure at the end of the day)	
Ibrahim et al. [141]	2019	VR	44	The study examined how mood states influence human evaluations of thermal environments in virtual settings.	No	-	**mood states** (anger, happiness**) Operative temperatures** (15°C, 21°C, and 27°C) **Virtual settings** (a domestic environment and a public workspace)	Mood states significantly affect how humans perceive and evaluate their thermal environment. Negative moods amplify perceived thermal discomfort, while positive moods can attenuate it, especially when combined with appropriate virtual settings.
Chamilothori et al. [88]	2019	Field Experiment &VR	29	The study aims to evaluate the adequacy of IVR as a method for assessing the perception of daylit spaces, comparing real and virtual environments in terms of perceived pleasantness, interest, excitement, complexity, and satisfaction with the amount of view in the space.	Yes	**Survey Responses** **Statistical Analysis (**Wilcoxon signed ranks tests)	**Perceptual aspects** (pleasantness, interest, excitement, complexity, and satisfaction with the view)	The study finds that IVR offers a high level of perceptual accuracy for evaluating daylit spaces, with no significant differences between the real and virtual environments. Furthermore, there was a high perceived presence in the virtual environment, and no significant physical symptoms were reported after using the VR headset.
Abd-Alhamid et al. [108]	2019	Field Experiment & VR	20	The aim of the study was to evaluate differences in visual	Yes	**Survey Responses**	**Task Performance View Quality perception**	The study finds no significant differences between real and virtual environments in terms of visual perception, indicating that VR

				perception between real and virtual environments, using a comprehensive set of criteria.		**Physical Measurements** **Statistical analyses** (RMSE (Root Mean Square Error) and MAD (Mean Absolute Deviation))	(Contrast, Colour, Colour Variety) **Lighting Appearance** **Room Impressions** **Realness** **Spatial Presence** **Involvement** **Simulator Sickness Symptoms** **Stress and Affect Levels**	is a promising tool for realistically simulating luminous environments.
Salamone et al. [101]	2020	Field Experiment & VR	25	The study aims to investigate the effect of visual stimuli on personal thermal comfort perception by comparing feedback from participants exposed to real-world and virtual scenarios.	Yes	**Survey Responses** **Physical Measurements** **Statistical Analysis** **Machine Learning (ML)** (Extra Trees Classifier, Logistic Regression, Linear Discriminant Analysis, Decision Trees,	**biometric data** (heart rate, EDA, Tskin) **Environmental variables** (temperature, humidity, air speed) **Personal feedback on thermal comfort**	The study finds that VR is a valid approach to assessing personal thermal comfort. Machine learning models, particularly the Extra Trees Classifier, can accurately predict participants' thermal comfort perception in real and virtual scenarios.

						Support Vector Machines, and Random Forests)		
Moscoso et al. [102]	2020	VR	150	The aim was to examine how different window sizes affect the perception of spaces at high latitudes, including how these impressions are influenced by factors such as sky type, context, and space type.	No	-	Window Size Space Size Context Scenarios **Sky Types**	Larger windows were associated with more positive evaluations across various attributes, including the view amount, spaciousness, and overall perception. The study also found an interaction between window size and space type for satisfaction with the view amount.
Abd-Alhamid et al. [87]	2020	VR	32	To evaluate the impact of viewing position on view perception and its restorative benefits in a virtual environment with a window view.	No	-	View Access: viewing location (close, middle, far) view characteristics: (content, quality, and size)	The study found that closer viewing positions led to higher view quality, with significant differences in subjective and physiological parameters. This indicates that distance from the window impacts restorative benefits and overall view perception. This suggests that window design and placement are crucial to occupant well-being in built environments.
Flor et al. [84]	2021	VR	22	The aim of the study was to investigate the user acceptance of energy-saving retrofitting measures in office buildings, particularly focusing	No	-	View Clarity: Different ETFE façades (clear, fritted, and switchable) and a reference double-glazed window.	The study found that view clarity and view satisfaction were highest for the reference double-glazed window. Clear ETFE double-skin façades had better ratings than fritted and switchable variants, highlighting the importance of view clarity for user acceptance. The study concluded that ETFE

				on view perception and emotional responses towards ETFE double-skin façades.				façades could play a crucial role in building energy retrofitting, though their design must carefully balance energy efficiency with view clarity and user satisfaction.
Carneiro et al. [142]	2019	IVE	120	The aim was to understand participants' lighting choices and their influence on energy consumption, focusing on variables like room orientation, time of day, and use of blinds.	No	-	Time of day Room orientation (north or south) **Blind state** (fully open, 25% open, 50% open, 75% open, and fully closed) **Artificial lighting** (0, 1, 2, or 3 bulbs on)	The study found that participants' lighting choices were influenced by time of day and room orientation and that these choices led to significant energy savings compared to baseline energy consumption, particularly in the north-facing office.
Oh and Son [143]	2022	VR	154	This study aims to analyze the degree of cybersickness based on various attributes of VR content and generate a dataset for cybersickness prediction models.	No	**-**	**Subjective opinions** (cybersickness scores and SSQ) **Biological signals** (EEG, ECG, and GSR)	Various content factors influence cybersickness, including camera movements, FOV, and controllability. The study also revealed that physiological features, such as EEG power densities, can reflect cybersickness severity, and individual characteristics like age and susceptibility also play a role.
Ko et al. [82]	2023	VR	40	The study aimed to assess the effect of geometric variables (view angles, glazing area, window distance, viewing direction, and PWV) on occupant	No	-	Horizontal and vertical view angles Window distance Viewing direction Percentage of window view area in the visual field WWR	The study found that glazing area (WWR), window distance, and viewing direction are the primary predictors of satisfaction with view access. It also developed a view access index and recommended a minimum WWR of 25% and saturation of 65% to promote occupant satisfaction.

				satisfaction regarding view access and develop a view access index.				
Kojima et al. [103]	2023	Field Experiment and VR	15	To develop a window view quality index for application at the design stage of office buildings, and to assess the validity of using VR for evaluating window views.	Yes	Survey Responses Physical Measurements Correlation Analysis	View Access: Floors (4th, 6th, and 9th), distances from the window (1.2m, 2.7m, 7.5m), and proportion of view content (sky, green, buildings).	There is a high correlation between real-world and VR evaluations of window views, suggesting VR can be effectively used in planning window designs.
Abd-Alhamid et al. [81]	2023	VR	25	The aim of the study is to investigate the influence of window size and layout on view quality perception, stress recovery, and physiological and psychological effects in a VR environment.	No	-	View Access: Window size and layout View Perception Stress Recovery Physiological responses (e.g., skin conductance, heart rate variability) Psychological effects	The study found that larger window sizes and wide orientations generally led to higher view quality perception, increased stress recovery, and improved psychological affect, indicating the importance of considering view perception for occupant well-being when designing window openings.

Appendix D: Initial Pilot Test, Challenges and Solutions

A pilot test was conducted involving 10 participants to evaluate initial user experience and procedural effectiveness. This Pilot study done deploying four selected BIPV window configurations: Configuration 3 (1/1, 0.48), Configuration 6 (1/2, 0.48), Configuration 9 (1/3, 0.48), and a clear reference window (Configuration 0). The pilot aimed to identify potential procedural, technical, and participant comfort issues to refine the experimental approach. (see Table 24)

Table 25. Pilot Study Challenges and Implemented Solutions

Technical/User-Related Challenges	Implemented Solution
Confusion about Study Objectives	Structured five-minute pre-instruction session
Scale Clarity	Standardized numeric scale (-3 to +3)
Immediate Response Issues	Introduced 2–3-minute acclimation period
Data Recording Accuracy	Implemented voice recordings
Insufficient Visual Realism	Improved textures, reflectivity, and lighting
Environmental Inconsistency	Conducted testing between 10 am and 2 pm

Several challenges emerged during this pilot phase, addressed through target refinement:

Understanding the Study Objectives: Initially, as participants entered the IVR environment, I noticed uncertainty regarding what they were expected to evaluate. Participants sometimes asked for clarification. Informal discussions after sessions revealed misunderstandings about the evaluation parameters, specifically what constituted "view clarity," "view privacy," and "overall satisfaction." To resolve this, I implemented a structured five-minute pre-instruction session prior to the evaluation. This included clear definitions and examples for each evaluation criterion, such as explaining "view clarity" "view privacy", and "overall satisfaction" with the BIPV window configuration. Additionally, I clearly demonstrated the meaning of the numeric ratings

from -3 (very dissatisfied) to +3 (very satisfied), enhancing participants' confidence and improving the accuracy of responses.

Response Scale Consistency: During initial tests, participants expressed difficulty distinguishing clearly between verbal descriptions like "very satisfied" or "very dissatisfied." Observing their confusion, I revised the scale to a numeric range from -3 (very dissatisfied) to +3 (very satisfied). This simple numerical approach significantly eased participant comprehension, allowing quicker and more consistent responses.

Acclimation to IVR Environment: I observed participants initially provided inconsistent answers when questioned immediately after entering the virtual environment. Participants mentioned feeling disoriented at first and needing time to adjust. Recognizing this, I introduced a 2–3 minutes involvement period at the beginning of each session. During this period, participants had time to immerse themselves in the virtual environment, which improved the consistency of their responses.

Accurate Data Recording: During initial data collection, manually transcribed responses occasionally led to errors. To improve accuracy, I incorporated voice recordings during each session, ensuring precise data transcription and significantly reducing the risk of manual entry errors.

Visual Realism Enhancements: Few participants mentioned issues regarding realism, particularly in the rendering of textures and the windowsill height within the virtual environment. Taking this feedback into consideration, I adjusted material properties, improved texture resolutions, and refined the windowsill in the model within the IVR setup. Subsequent participants immediately recognized and positively noted these improvements, which enhanced their immersive experience.

Environmental Consistency: Midway through testing, I noticed room temperature fluctuations significantly after 2 pm, potentially affecting participant comfort and responses. To maintain a consistent testing environment, I restricted all study sessions to a daily window from 10 am to 2 pm, conducted consistently over two weeks in March.