

**DEVELOPMENT OF SUSTAINABILITY ASSESSMENT
FRAMEWORK FOR SMART GLAZING IN NON-
DOMESTIC BUILDINGS**

BY

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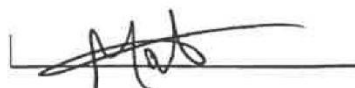
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To my parents, whose prayers and support have been my greatest strength, and to my family, friends, and teachers for their encouragement throughout this journey. |

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TABLE OF CONTENTS

ACKNOWLEDGMENTS.....	v
TABLE OF CONTENTS.....	vi
LIST OF TABLES.....	x
LIST OF FIGURES	xii
LIST OF ABBREVIATIONS	xiv
ABSTRACT	xv
ملخص الرسالة.....	xvii
1 CHAPTER 1 INTRODUCTION.....	1
1.1 Background and Role of Smart Glazing in Sustainable Buildings	1
1.2 Research Gap.....	3
1.3 Problem Statement.....	6
1.4 Research Aim and Objectives.....	8
1.5 Research Questions	9
1.6 Research Limitations and Boundaries	10
1.7 Significance of the Research	12
1.8 Thesis Organization	13
1.8.1 Chapter 1. Introduction	13
1.8.2 Chapter 2. Literature Review	14
1.8.3 Chapter 3. Methodology	14
1.8.4 Chapter 4. Results and Discussion	14
1.8.5 Chapter 5. Conclusion and Future Recommendations	15
2 CHAPTER 2 LITERATURE REVIEW	16
2.1 Smart Glazing Technologies: Overview and Types.....	16
2.1.1 Active Smart Glazing Technologies	18
2.1.2 Passive Smart Glazing Technologies.....	24
2.1.3 Summary.....	27
2.2 Sustainability	28
2.2.1 Sustainability Assessment and Frameworks	29
2.2.2 Previous Research on Sustainability Assessment	30

2.2.3	Sustainability Potential of Smart Glazing	33
2.2.4	Smart Glazing in Hot Climate: Potential and Sustainability for Non-Domestic Buildings	38
2.3	Sustainable Smart Glazing System Selection Using MCDM.....	40
2.3.1	Subjective Weighting (Likert Scale Approach).....	41
2.3.2	Shannon Entropy Method for Objective Weighting	42
2.3.3	TOPSIS.....	43
2.3.4	Normalization Techniques in MCDM	45
3	CHAPTER 3 METHODOLOGY.....	50
3.1	Overview of Methodological Approach	50
3.2	Systematic Literature Review: Identification of Criteria	57
3.2.1	Objective.....	58
3.2.2	Search Strategy	58
3.2.3	Inclusion and Exclusion Criteria	60
3.2.4	Screening and Selection	62
3.2.5	Data Extraction.....	64
3.2.6	Data Synthesis.....	65
3.3	Questionnaire (S5): Validation and Prioritization of Criteria	71
3.3.1	Purpose of the Questionnaire	72
3.3.2	Questionnaire Structure and Design.....	73
3.3.3	Survey Implementation/ Survey Approach and Expert Sampling.....	75
3.3.4	Analysis of Survey Results and Data Interpretation	78
3.4	Data Collection for Decision Matrix (S7)	81
3.4.1	Identification and Selection of Smart Glazing Alternatives	83
3.4.2	Case Study Description.....	86
3.4.3	Calibration Methodology for the Simulation Model	89
3.4.4	Simulation Setup for Smart Glazing Systems	92
3.4.5	Assessment of Environmental Performance	97
3.4.6	Assessment of Social Performance	100
3.4.7	Assessment of Economic Performance	115

3.4.8	Assessment of Technical Performance.....	119
3.5	Decision Model Development.....	123
3.5.1	Development of Decision Matrix.....	125
3.5.2	Classification of Sub-Criteria.....	125
3.5.3	Normalization of Decision Matrix.....	125
3.5.4	Objective Weight Calculation for Sub-Criteria	128
3.5.5	Subjective Weight Calculation for Main Criteria	129
3.5.6	TOPSIS Application	131
4	CHAPTER 4 RESULTS AND DISCUSSION	135
4.1	Results of the Systematic Literature Review	135
4.1.1	Bibliometric Overview of Selected Studies	136
4.1.2	Overview of Study Characteristics	141
4.2	Sustainability Criteria Analysis.....	143
4.2.1	Curated and Categorized Criteria.....	143
4.2.2	Relevance to Sustainability	147
4.2.3	Criteria Relationship and Impact Analysis	152
4.3	Questionnaire Results and Analysis	158
4.3.1	Profile of Questionnaire Respondents	159
4.3.2	Adequacy of Sample Size.....	162
4.3.3	Ranking Data Analysis of Questionnaire Responses/ Ranking Analysis.....	162
4.3.4	Summary and Final Criteria Hierarchy	176
4.4	Selected Alternatives of Smart Glazing	178
4.5	Hierarchical Model	180
4.6	Data Collection Results	181
4.6.1	Calibration of the Model	181
4.6.2	Environmental Performance Results	183
4.6.3	Social Performance Results	192
4.6.4	Economic Performance Results	214
4.6.5	Summary of Economic Performance.....	218

4.6.6	Technical Performance Results	219
4.6.7	Summary of Technical Performance	225
4.7	Multi-Criteria Decision Model Results	226
4.7.1	Final Decision Matrix.....	226
4.7.2	Criteria Classification.....	229
4.7.3	Normalized Decision Matrix	231
4.7.4	Entropy Weighting.....	232
4.7.5	Subjective Weighting.....	235
4.7.6	Global Weights	237
4.7.7	Weighted Normalized Decision Matrix	239
4.7.8	TOPSIS Ranking	240
4.8	Verification of the SG-SAF Framework	243
4.8.1	Expert-Driven Criteria Validation and Prioritization	244
4.8.2	Simulation-Based Performance Verification with Real Data	245
4.8.3	Robust Weighting Methodology and MCDM Consistency	246
4.8.4	Summary.....	248
5	CHAPTER 5 CONCLUSION.....	249
5.1	Conclusion	249
5.2	Future Recommendations.....	256
	References	257
	Appendix 1	270
	Appendix 2	279
	Appendix 3	281
	Appendix 4	295
	Vitae.....	297

LIST OF TABLES

Table 1: Comparison of normalization methods	49
Table 2: Research objectives, questions, methods, and expected outcomes	55
Table 3: Research protocol for SLR.....	60
Table 4: Inclusion and exclusion criteria for systematic literature review.....	62
Table 5: Comprehensive curation summary.....	69
Table 6: Importance level based on RII values [111, 112]	80
Table 7: Selected smart glazing alternatives	85
Table 8: Physical characteristics of the case study.....	87
Table 9: Floor-wise zoning, occupancy, and glazing orientation	88
Table 10: Calibration criteria of ASHRAE guidelines 14 [122]	90
Table 11: Simulation parameters and controls	93
Table 12: Floors and zones with active lighting control and sensor placement.....	95
Table 13: Daylighting simulation parameters	102
Table 14: Glare classification based on the Daylight Glare Index (DGI) scale [125] ...	103
Table 15: sDA300lx rating criteria based on LEED4.1	105
Table 16: Environmental input parameters for thermal comfort analysis.....	108
Table 17: Categories of thermal environments according to ISO 7730 [136]	110
Table 18: Reference STC values (dB) for smart glazing alternatives	115
Table 19: Rubric for commercial maturity evaluation	123
Table 20: Bibliometric characteristics of identified studies.....	137
Table 21: LEED and BREEAM visual comfort and daylighting parameters	149
Table 22: Summary sustainability relevance.....	152
Table 23: Environmental sub-criteria and their relationship to smart glazing selection	154
Table 24: Social sub-criteria and their relationship with smart glazing selection.....	155
Table 25: Economic sub-criteria and their relationship to smart glazing selection	157
Table 26: Technical Sub-Criteria and Their Relationship with Smart Glazing Selection	158
Table 27: Rating responses of 22 respondents for criteria and sub-criteria	164
Table 28: Summary of main sustainability criteria rankings analysis.....	166
Table 29: Summary of sub-criteria rankings analysis under the environmental dimension	169
Table 30: Summary of sub-criteria rankings analysis under the social dimension	172
Table 31: Summary of sub-criteria rankings analysis under economical dimension.....	174
Table 32: Summary of sub-criteria rankings analysis under technical dimension.....	175
Table 33: Summary of expert comments, revisions, and justifications.....	175
Table 34: Final sustainability criteria and sub-criteria identified through SLR.....	178
Table 35: Selected smart glazing alternatives	179
Table 36: Measured vs. simulated monthly energy consumption and calibration metrics	182

Table 37: Annual energy consumption and savings for smart glazing alternatives (KWh/yr)	184
Table 38: Annual energy consumption per m ²	184
Table 39: Environmental sustainability ranking of smart glazing alternatives	191
Table 40: Visible Light Transmittance of smart glazing alternatives in fully tinted state	194
Table 41: Glare index for floor 7 zone 4	195
Table 42: Spatial daylight autonomy of smart glazing alternatives compared to base case.	197
Table 43: Average UDI _{100–3000 lux} , 50% for smart glazing alternatives	198
Table 44: Daylight Factor (DF) for smart glazing alternatives	200
Table 45: SHGC, U-value, and LSG values of smart glazing alternatives	203
Table 46: Monthly PMV values and summer averages for smart glazing alternatives..	205
Table 47: Monthly PPD values and summer averages for smart glazing alternatives ...	206
Table 48: Annual window heat gain (kWh)	208
Table 49: Monthly Indoor operative temperature (°C)	209
Table 50: STC values for selected smart glazing alternatives	211
Table 51: Comparative Summary of Social Performance Across Smart Glazing Alternatives	213
Table 52: Initial cost estimates of Smart glazing alternatives	215
Table 53: Cooling cost savings of smart glazing alternatives	216
Table 54: Total energy cost savings of smart glazing alternatives	217
Table 55: Payback period of smart glazing technologies	218
Table 56: Economic sustainability ranking	219
Table 57: Operational performance of smart glazing alternatives	220
Table 58: Commercial maturity assessment results	225
Table 59: Technical performance standardized data for decision matrix	225
Table 60: Final decision matrix for smart glazing alternatives	227
Table 61: Classification of sub-criteria as cost or benefit	229
Table 62: Normalized decision matrix	231
Table 63: Entropy weights of sub-criteria	233
Table 64: Subjective weights of main criteria	236
Table 65: Global weights for sub-criteria	238
Table 66: Weighted normalized decision matrix	239
Table 67: Positive ideal solution and negative ideal solution values for each sub-criterion	240
Table 68: Results of TOPSIS	242
Table 69: Detailed profile of survey respondents	295

LIST OF FIGURES

Figure 1: Research gap and response map	4
Figure 2: Boundaries and limitations of study	12
Figure 3: Classification of smart glazing materials	18
Figure 4: (a) Structure and (b) working mechanism of electrochromic glazing	19
Figure 5: Tinting states of electrochromic (EC) glazing	20
Figure 6: PDLC glazing in OFF and ON states	22
Figure 7: (a) Structure and (b) working mechanism of thermochromic glazing	25
Figure 8: Photochromic glazing response to daylight conditions throughout the day	27
Figure 9: Projected growth of the smart glass market in different regions (2023-2030).	40
Figure 10: Methodological flowchart	54
Figure 11: Systematic literature review (SLR) workflow	57
Figure 12: PRISMA flowchart	63
Figure 13: Extracted data format	65
Figure 14: Data synthesis	66
Figure 15: Schematic showing classification of criteria under four sustainability dimensions	70
Figure 16: Methodological overview of questionnaire survey	72
Figure 17: Methodological overview for performance data collection	82
Figure 18: Case study: (a) Simulated model in Design builder, (b) Real building image	86
Figure 19: Floor plans of the building (a) Ground floor, (b) Mezzanine floor, (c) Typical first to seventh floors, (d) Fifth floor, (e) Eight floor	88
Figure 20: Calibration process of the model	91
Figure 21: Methodological overview of decision model development	124
Figure 22: Rationale of vector normalization selection	127
Figure 23: Overview of studies	140
Figure 24: Frequency of occurrence of smart glazing	142
Figure 25: Distribution of building types in studies	142
Figure 26: Geographical distribution of studies	143
Figure 27: Curated and categorized sustainability criteria	146
Figure 28: Geographic distribution of survey respondents	160
Figure 29: Distribution of respondents by organization type	160
Figure 30: Experts' validated hierarchy	180
Figure 31: The model's measured versus simulated monthly energy consumption after calibration	182
Figure 32: CVRMSE and NMBE values compared to ASHRAE limits	183
Figure 33: Heating energy consumption (KWh/yr) for smart glazing alternatives	186
Figure 34: Cooling energy consumption (kWh/yr) for smart glazing alternatives	187
Figure 35: Artificial energy consumption (kWh/yr) for smart glazing alternatives	188
Figure 36: Total energy consumption (kWh/yr) for smart glazing alternatives	189
Figure 37: CO2 Emissions and mitigation potential for smart glazing alternatives	190

Figure 38: Simulated glare index value for smart glazing alternatives	196
Figure 39: Weighted Average UDI100 lux – 3000 lux (%)	199
Figure 40: Weighted average Uniformity Daylight Factor (UDF) for smart glazing alternatives.....	202
Figure 41: Monthly PMV values in comparison with ISO 7730 recommended comfort range	205
Figure 42: Annual window heat gain (kWh/year. m2).....	208
Figure 43: LSG ratio of smart glazing alternatives.....	210
Figure 44: Verification aspects of SG-SAF.....	244

LIST OF ABBREVIATIONS

ASHRAE	:	American Society of Heating, Refrigerating and Air-Conditioning Engineers
BREEAM	:	Building Research Establishment Environmental Assessment Method
CFD	:	Computational Fluid Dynamics
CVRMSE	:	Coefficient of Variation of Root Mean Square Error
DA	:	Daylight Autonomy
DF	:	Daylight Factor
DGI	:	Daylight Glare Index
EC	:	Electrochromic
GC	:	Gasochromic
ISO	:	International Organization for Standardization
LEED	:	Leadership in Energy and Environmental Design
LED	:	Light Emitting Diode
LSG	:	Light to Solar Gain ratio
MCDM	:	Multi-Criteria Decision Making
NMBE	:	Normalized Mean Bias Error
PDLC	:	Polymer Dispersed Liquid Crystal
PMV	:	Predicted Mean Vote
PPD	:	Predicted Percentage Dissatisfied
PRISMA	:	Preferred Reporting Items for Systematic Reviews and Meta-Analyses
RII	:	Relative Importance Index
SLR	:	Systematic Literature Review
SHGC	:	Solar Heat Gain Coefficient
SPD	:	Suspended Particle Device
STC	:	Sound Transmission Class
TC	:	Thermochromic
TOPSIS	:	Technique for Order of Preference by Similarity to Ideal Solution
TT	:	Thermotropic
UDI	:	Useful Daylight Illuminance
UDF	:	Uniformity Daylight Factor
VLT	:	Visible Light Transmittance

ABSTRACT

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Smart glazing technologies have emerged as promising solutions for enhancing energy efficiency, indoor environmental quality, and user comfort in buildings. Their dynamic response to solar conditions makes them especially valuable in hot climates, where reducing cooling loads and improving daylight performance are essential to sustainable design. However, despite their potential, the selection of suitable smart glazing systems remains fragmented due to the absence of a unified framework that evaluates sustainability holistically across environmental, social, economic, and technical dimensions. This study addresses this gap by developing a Sustainability Assessment Framework for Smart Glazing (SG-SAF) tailored for non-domestic buildings in hot climatic regions. The framework integrates validated sustainability criteria with performance-based and expert-informed evaluation through a structured, data-driven approach. A multi-phase methodology was adopted, beginning with a systematic literature review to identify relevant criteria, followed by expert validation using Likert-scale surveys, simulation of performance metrics via a calibrated energy model, and application of multi-criteria decision-making (MCDM) techniques. A hybrid weighting scheme was used, combining objective weights (Shannon Entropy) and subjective expert inputs, with the TOPSIS method employed to rank seven smart glazing alternatives. The results show that SG-SAF enables a comprehensive and transparent comparison of alternatives, capturing both

qualitative and quantitative dimensions. The top-ranked options demonstrated not only high energy and daylight performance but also social and economic feasibility. The framework's applicability was further confirmed through simulation results and expert feedback, affirming its robustness for real-world decision-making. This study contributes a novel, context-sensitive methodology for sustainable material selection and supports the advancement of resource-efficient, user-oriented, and climate-responsive design in line with national priorities such as Saudi Vision 2030 and international goals like the UN Sustainable Development Goals.

ملخص الرسالة

الاسم الكامل: غنوة نعيم
عنوان الرسالة: تطوير إطار تقييم الاستدامة للزجاج الذكي في المباني غير السكنية
التخصص: الهندسة المعمارية
تاريخ الدرجة العلمية: مايو 2025

ظهرت تقنيات الزجاج الذكي كحلول واعدة لتعزيز كفاءة الطاقة وجودة البيئة الداخلية وراحة المستخدمين في المباني. وتتميز هذه التقنيات بقدرتها الديناميكية على التفاعل مع الظروف الشمسية المتغيرة، مما يجعلها ذات قيمة عالية في المناطق الحارة، حيث يُعد تقليل أحمال التبريد وتحسين أداء الإضاءة الطبيعية من المتطلبات الأساسية للتصميم المستدام. ومع ذلك، ورغم هذا الإمكانيات، لا يزال اختيار أنظمة الزجاج الذكي المناسبة مجزأً نتيجة لغياب إطار موحد يقيم الاستدامة بشكل شامل عبر الأبعاد البيئية، والاجتماعية، والاقتصادية، والتقنية. تهدف هذه الدراسة إلى سد هذه الفجوة والمصمم خصيصاً للمباني غير السكنية في (SG-SAF) "من خلال تطوير "إطار تقييم الاستدامة للزجاج الذكي المناطق ذات المناخ الحار. يدمج هذا الإطار معايير استدامة مُتحقق من صحتها مع تقييم قائم على الأداء وآراء الخبراء من خلال منهجية منهجية مبنية على البيانات. اعتمدت الدراسة على منهجية متعددة المراحل، بدأت بمراجعة منهجية للأدبيات لاستخلاص المعايير ذات الصلة، تلتها عملية تحقق من خلال استبيانات تعتمد على مقياس "ليكرت"، ثم محاكاة ، ثم استخدام MCDM أداء البدائل باستخدام نموذج طاقة مبنى مُعَيَّر، وأخيراً تطبيق تقنيات اتخاذ القرار متعدد المعايير أسلوب ترجيح هجين يجمع بين الأوزان الموضوعية (طريقة شانون إنتروبي) والمدخلات الذاتية للخبراء، مع استخدام يمكن من مقارنة شاملة SG-SAF لترتيب سبعة بدائل للزجاج الذكي. وأظهرت النتائج أن إطار TOPSIS طريقة وشفافة للبدائل، حيث أظهرت الخيارات الأعلى تصنيفاً أداءً متميزاً ليس فقط من حيث الطاقة والإنارة الطبيعية، بل أيضاً من حيث القبول الاجتماعي والجدوى الاقتصادية. تم التحقق من قابلية تطبيق الإطار من خلال المحاكاة وتعليقات الخبراء، مما يؤكد تماسكه وفعاليته في المساعدة في اتخاذ قرارات التصميم الواقعية. تسهم هذه الدراسة في تطوير منهجية مبتكرة وحساسة للسياق لاختيار المواد المستدامة، وتدعم التوجه نحو تصميم يستجيب للمناخ ويركز على المستخدم ويحقق الكفاءة في استخدام الموارد، بما يتماشى مع رؤية السعودية 2030 وأهداف التنمية المستدامة للأمم المتحدة.

CHAPTER 1

INTRODUCTION

1.1 Background and Role of Smart Glazing in Sustainable Buildings

The global population reached 8 billion in 2022, with 55% (4.4 billion) of people residing in urban areas. By 2050, this proportion is expected to rise substantially to nearly 70% [1, 2]. This rapid urbanization presents severe sustainability challenges, including air pollution, depletion of natural resources, increased energy consumption, and substantial waste generation [3]. Consequently, the total floor area of buildings is anticipated to expand significantly, with approximately 80% of this growth occurring in emerging and developing economies by 2030 [4]. As a result, there will be a parallel rise in the demand for advanced building services and improved indoor comfort, leading to greater energy use and operational emissions, particularly in residential and commercial buildings [5].

According to the International Energy Agency (IEA), the building sector is the biggest energy consumer worldwide, significantly contributing to direct and indirect carbon dioxide (CO₂) emissions [4]. Buildings currently account for approximately one-third of the global energy demand to maintain indoor environments within comfortable ranges. The IEA's 2021 report indicates that building energy consumption increased from 115 EJ in 2010 to 135 EJ in 2021, with building operations responsible for 30% of the world's final total energy consumption. Consequently, the energy-related CO₂ emissions from buildings are a major contributor to climate change [5, 6]. Moreover, the World Green Building Council (WGBC) reports that buildings contribute 39% of global carbon emissions, with 28% stemming from operational activities such as heating, cooling, and electricity use,

while the remaining 11% results from materials and construction processes [6]. These statistics highlight the urgent need for sustainable building solutions to mitigate climate change. According to WGBC, sustainable buildings could potentially reduce energy consumption by 50% by 2050 [7]. Moreover, the expansion of the construction sector is creating new opportunities for integrating energy-efficient technologies, driving the adoption of innovative, low-carbon, and high-performance buildings [8].

In this context, smart glazing technologies have emerged as a promising solution for improving building performance, particularly in hot climates. By dynamically adjusting their light and heat transmittance based on external conditions, smart glazing systems reduce cooling loads, manage glare, and optimize daylight use, enhancing both energy efficiency and occupant comfort [9-11]. For instance, the National Renewable Energy Laboratory (NREL) reports that electrochromic glazing can reduce electricity demand by up to 49% and lighting costs by 51%, making it especially valuable in high-performance commercial buildings [12].

Several types of smart glazing, including electrochromic, Suspended Particle Device (SPD), Polymer-Dispersed Liquid Crystal (PDLC), thermochromic, and gasochromic, have been extensively studied for their potential to improve energy savings, daylighting, thermal comfort, and visual performance [13-18]. Broader studies have also evaluated glazing systems under general sustainability parameters or through energy simulation models [19-23]. In essence, these studies have been further discussed in a *later section*, highlighting their scope, strengths, and limitations. However, most existing research either focuses on isolated aspects, such as energy consumption or glare control, or relies on

generic criteria derived from green building certification systems. These approaches often overlook the dynamic nature of smart glazing and fail to assess its performance holistically.

To date, no dedicated framework exists that systematically integrates environmental, economic, social, and technical dimensions into the selection of smart glazing technologies. Moreover, the absence of expert-driven multi-criteria methodologies limits the ability of architects, designers, and decision-makers to objectively evaluate alternatives based on comprehensive sustainability indicators. The research gap is further elaborated in Sections 1.2 and in the systematic literature review analysis.

This study addresses these gaps by proposing a novel Sustainability Assessment Framework for Smart Glazing (SG-SAF), tailored to non-domestic buildings in hot climatic regions, such as Saudi Arabia. The framework incorporates both quantitative and qualitative performance indicators under four core sustainability dimensions, using a structured Multi-Criteria Decision-Making (MCDM) approach to support balanced, data-informed decisions. In regions where extreme climatic conditions intensify cooling demand and daylight control needs, smart glazing selection plays a pivotal role in reducing energy consumption, enhancing occupant well-being, and promoting long-term sustainability.

1.2 Research Gap

Significant studies have been conducted on smart glazing technologies and their sustainability evaluation for building applications, as mentioned in a later section. However, as previously noted, a critical research gap remains in the decision-making process for selecting the most sustainable smart glazing option. While existing studies primarily focus on energy savings, thermal comfort, or daylight performance, they lack a

comprehensive sustainability assessment that integrates environmental, social, economic, and technical considerations. Specifically, no unified framework systematically defines sustainability criteria across all sustainability domains, making it difficult to identify the most suitable smart glazing solution for different applications. The key research gaps are elaborated below (*Figure 1*):

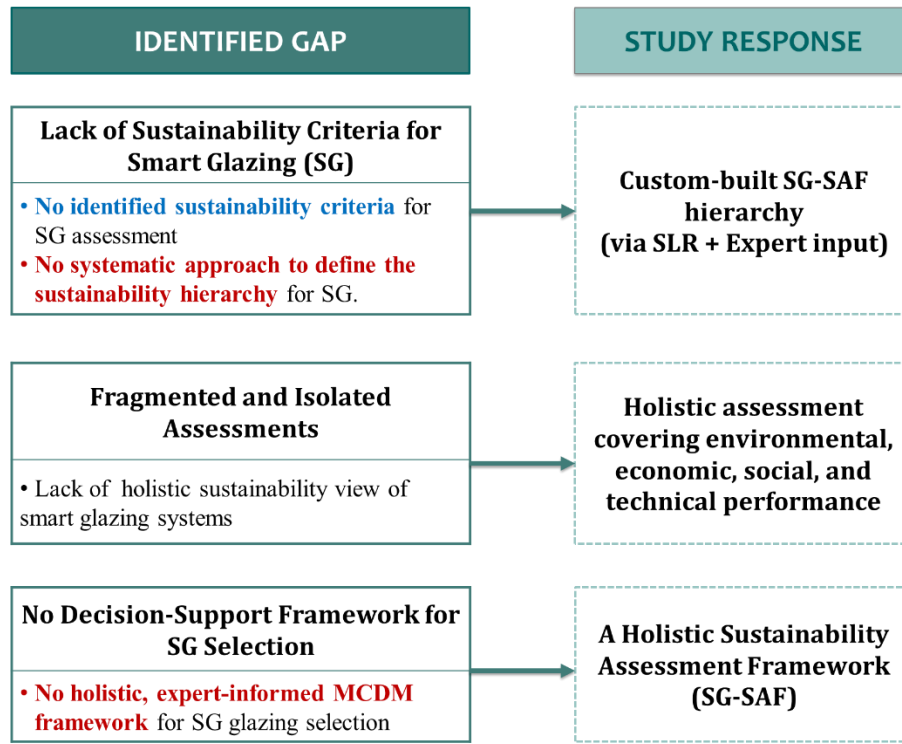


Figure 1: Research gap and response map

- **Lack of Sustainability Criteria for Smart Glazing Assessment**

Many sustainability assessments of smart glazing rely on predefined criteria from green building certification systems such as LEED, BREEAM, and Mostadam. While these standards provide general benchmarks for evaluating glazing performance, they do not specifically address the unique characteristics of smart glazing technologies. In many cases, smart glazing has not been studied as a distinct category but is instead assessed

alongside other advanced glazing options without a dedicated framework that accounts for its dynamic performance and adaptability [24, 25].

Furthermore, existing studies lack a structured methodology for systematically identifying, categorizing, and justifying the most relevant sustainability criteria for smart glazing technologies, particularly for hot climatic regions where cooling energy demand is a dominant concern. Without an established hierarchy of sustainability criteria, decision-makers face inconsistencies in evaluating smart glazing options.

To address this gap, this research develops a structured methodology for identifying and categorizing sustainability criteria specific to smart glazing technologies. By integrating expert input and systematically refining criteria, this study ensures a validated and transparent hierarchy that enhances decision-making for sustainable glazing selection.

- **Fragmented Focus on Isolated Aspects**

Most existing studies on smart glazing sustainability assessments focus on isolated performance aspects such as energy efficiency, daylighting, or visual comfort, without considering the interdependencies among environmental, economic, social, and technical factors. While energy savings and visual comfort are important, true sustainability assessment requires a holistic perspective that captures how these dimensions interact. Moreover, current assessments are often limited to specific building types or climatic conditions, making their application inconsistent across diverse environments. Many studies primarily evaluate smart glazing technologies within the context of high-performance glazing systems rather than as independent solutions, leading to gaps in understanding their full sustainability potential.

This research addresses these limitations by developing a Sustainability Assessment Framework for Smart Glazing (SG-SAF), which systematically incorporates and balances environmental, economic, technical, and social sustainability factors.

- **Absence of a Decision-Support Framework for Smart Glazing Selection**

Despite the growing interest in smart glazing technologies, no dedicated study systematically evaluates their selection based on comprehensive sustainability criteria. Existing research often examines smart glazing within broader high-performance glazing studies, failing to capture its unique adaptive functionalities. The absence of a tailored decision-support framework limits informed, and transparent selection aligned with sustainability objectives. This study develops a comprehensive selection framework that integrates environmental, economic, social, and technical dimensions using multi-criteria decision-making and expert input, ensuring a robust and practical approach to smart glazing selection.

This study develops a comprehensive selection framework that integrates environmental, economic, social, and technical sustainability dimensions using multi-criteria decision-making (MCDM) and expert input. The Sustainability Assessment Framework for Smart Glazing (SG-SAF) provides a scientifically robust and practical approach to smart glazing selection, ensuring structured and objective decision-making for sustainable building applications.

1.3 Problem Statement

The increasing global focus on sustainable development and energy efficiency in buildings has heightened the need for innovative solutions to mitigate the environmental impact of the built environment. Smart glazing technologies have emerged as a promising strategy

for reducing energy consumption, enhancing occupant comfort, and improving indoor environmental quality. However, despite extensive research on the performance of smart glazing, a critical gap remains in the decision-making process for selecting the most sustainable smart glazing solutions for non-domestic buildings in hot climatic region.

Existing studies predominantly focus on individual aspects of smart glazing performance, without integrating a comprehensive sustainability assessment that accounts for environmental, economic, social, and technical considerations of sustainability. Moreover, sustainability assessments of smart glazing often rely on predefined criteria from general green building rating systems (e.g., LEED, BREEAM, Mostadam), which do not fully capture the dynamic and adaptive nature of smart glazing technologies. Additionally, existing frameworks lack a structured and systematic methodology for identifying, categorizing, and prioritizing sustainability criteria specific to smart glazing, particularly in hot climatic regions.

Furthermore, there is no dedicated decision-support framework that facilitates the selection of smart glazing based on a holistic and structured sustainability assessment. Current research does not incorporate a unified Multi-Criteria Decision-Making (MCDM) approach to objectively evaluate smart glazing alternatives while considering expert perspectives from architects, designers, and construction professionals. The absence of such a framework limit informed decision-making, resulting in inconsistencies in smart glazing selection for non-domestic buildings.

To address this gap, this research develops the Sustainability Assessment Framework for Smart Glazing, designed specifically for non-domestic buildings in hot climatic regions, such as Saudi Arabia. This framework systematically integrates environmental, economic,

social, and technical sustainability dimensions while employing an MCDM-based approach to facilitate transparent and data-driven decision-making. By providing a structured methodology for assessing smart glazing solutions, the decision framework aims to enhance energy efficiency, occupant well-being, and sustainable urban development, aligning with Saudi Vision 2030 and global sustainability goals.

1.4 Research Aim and Objectives

The primary aim of this study is

“To develop a comprehensive Sustainability Assessment Framework (SG-SAF) for evaluating and selecting smart glazing technologies in sustainable building applications by systematically integrating environmental, economic, technical, and social sustainability dimensions.”

The developed framework will provide a structured, transparent, and validated approach to assessing smart glazing sustainability, supporting data-driven and objective decision-making for sustainable building applications, particularly in hot climatic regions. To achieve the primary aim of this study, the following specific objectives will be pursued:

1. To critically review existing sustainability assessment frameworks and decision-making methods for smart glazing technologies, identifying gaps and limitations.
2. To systematically identify, categorize, analyse, and synthesize sustainability assessment criteria for smart glazing technologies, ensuring a comprehensive evaluation of environmental, economic, technical, and social dimensions tailored to sustainable building applications.

3. To validate and prioritize sustainability criteria through expert consultation and statistical analysis, establishing a structured hierarchy that enhances decision-making effectiveness.
4. To develop and implement a Multi-Criteria Decision-Making (MCDM) framework (SG-SAF) for systematically assessing and ranking smart glazing technologies based on sustainability performance indicators.
5. To verify the SG-SAF framework by ensuring internal consistency and alignment with established sustainability principles, preparing it for future validation.

1.5 Research Questions

The study aims to answer the following key research questions:

1. What are the key sustainability criteria for assessing smart glazing in non-domestic buildings in hot climatic regions?
2. How can these criteria be systematically categorized and weighed for an effective decision-making framework?
3. How do expert perspectives and statistical analyses contribute to validating and prioritizing sustainability criteria for smart glazing evaluation?
4. How can a Multi-Criteria Decision-Making (MCDM) framework be structured to systematically integrate quantitative and qualitative sustainability indicators for smart glazing technologies?
5. How can the proposed Sustainability Assessment Framework (SG-SAF) be implemented to rank and select smart glazing alternatives based on sustainability performance?

6. How effective and applicable is the SG-SAF framework in real-world decision-making processes for sustainable buildings?

1.6 Research Limitations and Boundaries

The scope of this study is defined by the following limitations across its methodology, data sources, and analytical framework (*Figure 2*):

- **General limitations**

1. The Sustainability Assessment Framework for Smart Glazing (SG-SAF) is specifically developed for evaluating smart glazing technologies in non-domestic buildings situated in hot climatic regions. Its direct applicability to buildings in cold-dominant climates may be limited without climate-specific recalibration.
2. The study is limited to commercially available or well-documented smart glazing technologies. Experimental, under-development, or emerging glazing systems lacking sufficient empirical data were excluded to ensure robustness and comparability.

- **Systematic literature review limitations**

3. Despite the use of snowballing and forward referencing, some relevant studies may have been missed due to database access restrictions, language limitations, or indexing inconsistencies, particularly with grey literature or regional publications. Following this there is the possibility of omission of some specific criteria.
4. The identification of sustainability criteria is grounded in a systematic literature review (SLR), restricting the initial pool of indicators to those documented in peer-reviewed and accessible sources. Although expert input was employed to refine and validate these criteria, unreported or unconventional indicators may have been omitted.

- **Expert survey limitations**

5. A targeted panel of 22 experts was consulted to validate and prioritize the sustainability criteria. Due to logistical constraints, the study prioritizes depth of insights over the breadth of expert participation.
6. Experts primarily represented academia and professional practice within the smart building and façade domains. Broader stakeholder views (e.g., end-users, policymakers, contractors) were not explicitly included due to time and scope constraints.

- **Performance data and decision framework Limitations**

7. Performance values for each smart glazing alternative are based on generalized characterization data from simulations, literature, and manufacturers. These values may vary across specific brands, models, and installation contexts.
8. Economic data (initial cost, installation cost, etc.) is derived from average market prices and available quotes. These may fluctuate significantly across regions, project scales, and over time.
9. The case study building used for simulations reflects typical dimensions, orientation, and use patterns for office buildings in hot climates. However, it does not account for the full variability of architectural forms or operational schedules.
10. Some simulation-based indicators (e.g., lighting energy, daylight autonomy, glare index) are sensitive to zone-specific factors, such as geometry, window size, and control assumptions. Although these were standardized for consistency, they may not capture the full range of real-world performance variability.

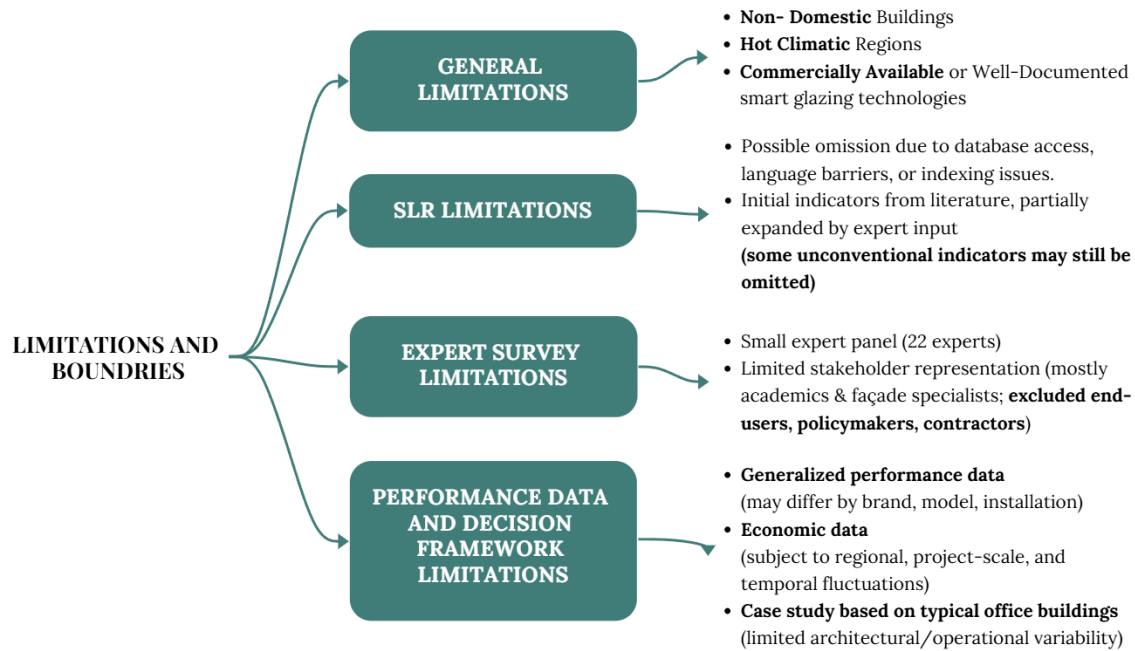


Figure 2: Boundaries and limitations of study

1.7 Significance of the Research

This study will hold substantial significance in the following key areas:

- **Advanced Knowledge and Research**

This research will contribute to the body of knowledge on smart glazing integration in buildings by conducting research to assess the sustainability of smart glazing, thereby developing a robust and holistic sustainability assessment framework that considers environmental and economic aspects. Further, the **SG-SAF** will furnish a reliable base for developing an AI-based application for evaluating and selecting smart glazing.

- **Industry Impact**

The SG-SAF will provide building designers and architects with a practical tool for selecting, comparing, and optimizing smart glazing technologies for new buildings that maximize sustainability in buildings. Moreover, building performance auditors and energy

consultants can utilize SG-SAF to assess the effectiveness of existing smart glazing installations and identify potential areas for improvement in terms of energy efficiency, occupant comfort, and overall sustainability.

- **Sustainable Buildings**

This research aligns with the UN Sustainable Development Goal 11 by promoting the development of energy-efficient and comfortable buildings. Therefore, the SG-SAF is expected to serve as valuable guidance for integrating innovative glazing technologies into sustainable building design and construction to meet energy efficiency challenges and environmental sustainability in the built environment.

- **Green Building Certification Programs**

Green building certification bodies and rating systems can incorporate SG-SAF as a valuable tool for evaluating the sustainability performance of smart glazing applications in buildings seeking certification, promoting wider adoption of these technologies.

1.8 Thesis Organization

This thesis consists of five chapters, each structured to build a coherent narrative for developing a **Sustainability Assessment Framework for Smart Glazing (SG-SAF)**. The chapters are outlined as follows:

1.8.1 Chapter 1. Introduction

This chapter introduces the background and context of the study, highlighting the growing importance of smart glazing technologies in sustainable building design. It outlines the research problems, aim, and objectives, and establishes the significance of developing a structured sustainability assessment framework. The chapter also defines the study's scope,

limitations, and potential contributions to academic research and practical decision-making.

1.8.2 Chapter 2. Literature Review

This chapter presents a comprehensive review of existing literature related to smart glazing technologies, sustainability assessment frameworks, and multi-criteria decision-making (MCDM) methods. It includes a preliminary literature review to identify the research gap and discuss the relevant concept of methodological techniques used in the study.

1.8.3 Chapter 3. Methodology

This chapter describes the methodological approach used to develop the SG-SAF. It includes the identification and refinement of sustainability criteria through SLR and expert consultation, followed by the collection of performance data from literature, manufacturer datasheets, and building simulations. The chapter also details the hybrid weighting process combining subjective expert ratings with objective Shannon Entropy calculations, and the application of the TOPSIS method for ranking smart glazing alternatives.

1.8.4 Chapter 4. Results and Discussion

This chapter presents and interprets the results of each research stage. It includes the outcomes of the SLR, expert survey, the performance analysis of smart glazing alternatives across the four sustainability dimensions, and the final rankings derived from the decision matrix using the TOPSIS method. The chapter concludes with a detailed validation of the SG-SAF through expert input, calibrated simulation data, and methodological alignment with established assessment frameworks.

1.8.5 Chapter 5. Conclusion and Future Recommendations

The final chapter summarizes the key findings of the study and reflects on the extent to which the research objectives were achieved. It outlines the practical implications of the SG-SAF for designers, policymakers, and researchers, and discusses the study's limitations. The chapter concludes with recommendations for future research, including the adaptation of the framework to different climates, integration of emerging technologies, and potential enhancements using dynamic performance monitoring and advanced decision-support systems.

CHAPTER 2

LITERATURE REVIEW

This chapter provides a critical examination and analysis of key concepts and findings identified from previous research. It serves as the theoretical foundation for the study by exploring the current state of knowledge related to smart glazing technologies, sustainability assessments, and multi-criteria decision-making (MCDM) methodologies. Initially, an overview of smart glazing technologies, including both active and passive systems, is presented to establish an understanding of their characteristics, operational mechanisms, and applications, particularly within non-domestic buildings situated in hot climatic regions. Subsequently, the concept of sustainability is explored, with an emphasis on frameworks and methodologies commonly employed for sustainability assessment in the built environment. This discussion leads to an analysis of previous research focused specifically on the sustainability potential of smart glazing solutions. Finally, the chapter critically evaluates the use of MCDM approaches as robust decision-support tools, highlighting their strengths and limitations in the context of sustainable building material selection. Through this structured literature review, the study identifies significant research gaps, establishes the context for the development of the proposed Sustainability Assessment Framework for Smart Glazing (SG-SAF), and underscores its relevance and necessity for advancing sustainable building practices.

2.1 Smart Glazing Technologies: Overview and Types

Smart glazing, also termed dynamic, intelligent, responsive, adaptive, or switchable glazing, is generally referred to as a glazing material whose optical and thermal properties can be actively or passively controlled or adjusted in response to the climate and the needs

of the occupants. These glazing materials can adjust solar heat gain, daylight transmission, and other optical characteristics in response to external stimuli such as heat, voltage, light, or an electrical current [13, 26]. It can dynamically adjust its transparency in response to stimuli to control the light and heat entering a building [27].

In sustainable architecture, smart glazing plays a pivotal role in improving energy efficiency and occupant comfort. By controlling the amount of solar heat entering a building, smart windows can reduce cooling loads in hot weather and improve thermal comfort for occupants. At the same time, they can maximize daylight usage, dimming excessive sunlight to prevent glare while still admitting enough natural light to lessen reliance on electric lighting. [20, 28]

Studies show that electrochromic (EC) smart windows, for example, can deliver significant energy savings, better visual comfort (through glare reduction), and maintain a connection to the outdoors by preserving views. In sum, integrating smart glazing into building design contributes to sustainability goals by lowering HVAC and lighting energy consumption and by enhancing the indoor environmental quality for occupants. As these technologies mature and costs decline, they are moving from niche early-adoption toward more mainstream use in modern green buildings. [29]

Smart glazing systems are broadly classified into active and passive categories based on how they are triggered and controlled, as illustrated in **Figure 3** [30]. Active smart glazing requires an external stimulus (usually an electrical voltage or current, or the injection of a chemical gas) to change its state [9, 31]. Passive smart glazing, by contrast, does not require any electrical power or active input; instead, it self-adjusts in response to environmental conditions such as ambient temperature or sunlight intensity. These passive systems undergo intrinsic material changes (in optical properties) when certain thresholds of

temperature or light are reached, without any user intervention or power supply. Passive systems are characterized by their simplicity, reliability, and ease of installation; however, they lack user control, which limits their adaptability to individual preferences or specific building requirements. [9, 31]

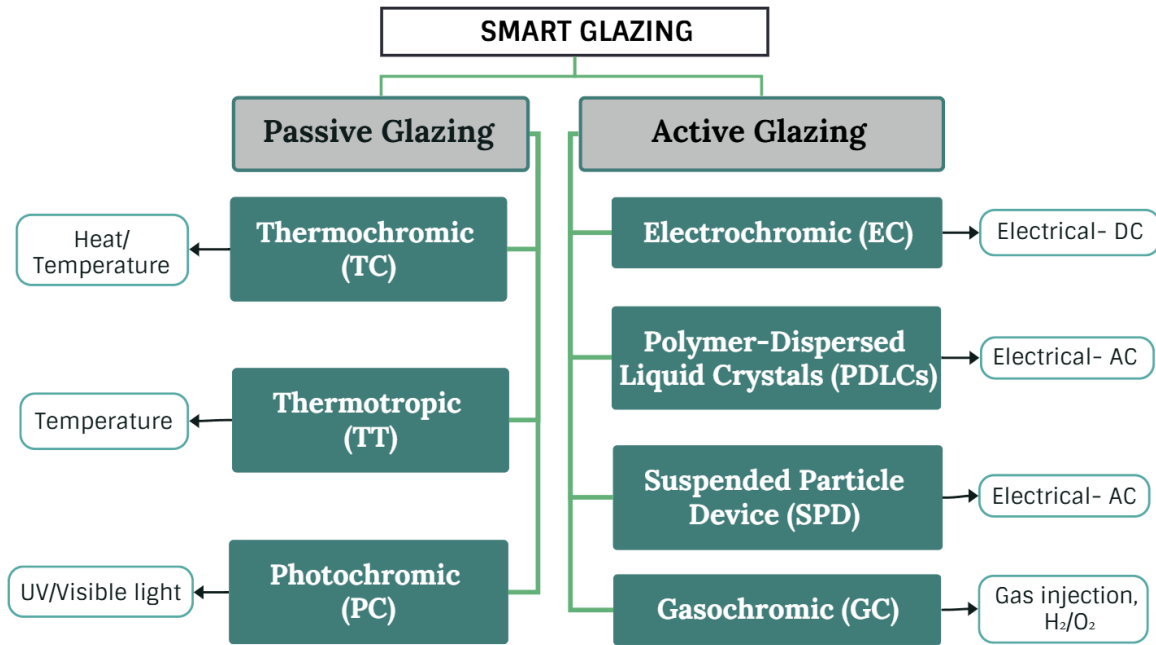


Figure 3: Classification of smart glazing materials [13]

2.1.1 Active Smart Glazing Technologies

Active smart glazing technologies require an external trigger (usually electrical) and generally allow on-demand control of the window's state. Below, the study reviews the major active technologies like electrochromic, suspended particle devices (SPD), polymer-dispersed liquid crystal (PDLC), and gasochromic, detailing their operating mechanisms, performance metrics, appearance, current use cases, and advantages/limitations.

2.1.1.1 Electrochromic Glazing

- **Mechanism and Stimulus**

Electrochromic (EC) glazing is an electrically switchable glass that changes its tint via a reversible electrochemical reaction in thin film coatings. Typically, an EC window consists of multiple layers: transparent conductive electrodes, electrochromic metal-oxide layers (often tungsten trioxide, WO_3), an ion storage layer, and an electrolyte. When a low DC voltage (on the order of 1–5 V) is applied between the electrodes, ions (e.g., Li^+ or H^+) migrate between the electrochromic layer and the counter layer, causing the electrochromic material to change oxidation state. This redox process alters the optical absorption of the coating; for example, WO_3 turns from transparent to blue-gray upon ion insertion (reduction). Reversing the voltage polarity drives the ions back and bleaches the window to clear. The stimulus is an electrical voltage, so electrochromic windows are an **active** system. The Structure and working mechanism of electrochromic glazing is shown in *Figure 4*. [30, 32]

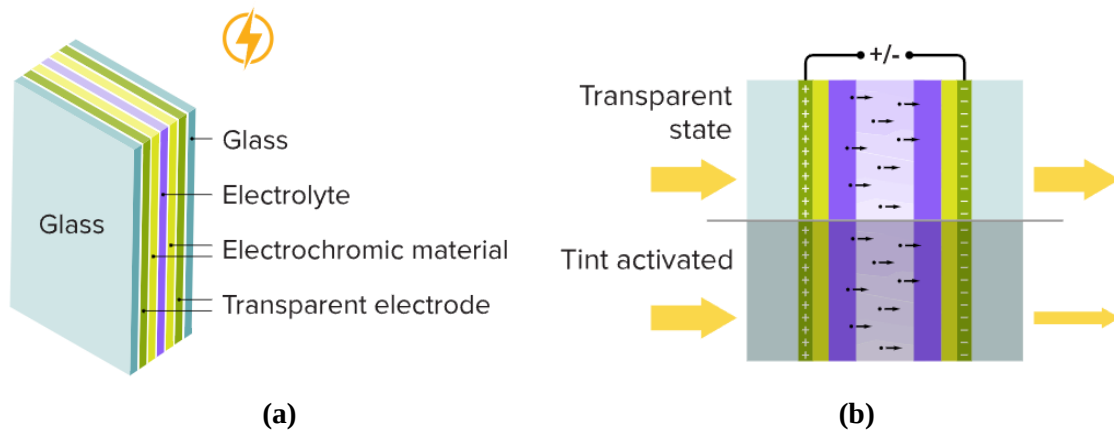


Figure 4: (a) Structure and (b) working mechanism of electrochromic glazing [33]

- **Switching Speed and Power**

Electrochromic (EC) glazing has evolved from early versions with slow, uneven tinting to newer generations offering uniform switching within 3 minutes for large panels. Typical

switching times range from a few seconds for small samples to 7–20 minutes for full-sized windows, with slower transitions providing visual comfort. ECs are bi-stable, consuming power only during switching and minimal or no power to maintain a given tint, making them highly energy-efficient. However, due to slower response times, control systems often anticipate lighting changes in advance. [30, 32, 34]

- **Appearance**

Electrochromic (EC) glazing typically has a slight bluish tint when darkened and may appear faintly yellowish when clear, though newer materials achieve more neutral-gray tones (**Figure 5**). Even in the tinted state, EC glass remains transparent, preserving outdoor views and daylight. Visible light transmittance (VLT) typically ranges from ~60–70% when clear to ~5–10% when fully tinted, depending on the specific product. [30, 32, 34]



Figure 5: Tinting states of electrochromic (EC) glazing

- **Commercial Availability**

Electrochromic (EC) glass is one of the most established smart glazing technologies, widely used in buildings and aircraft such as the Boeing 787. Products like SageGlass and View Dynamic Glass are commercially available worldwide, integrated into building management systems for dynamic daylight control. By 2025, EC glazing is no longer

limited to pilot projects and is increasingly adopted in high-profile, sustainability-driven buildings, supported by improving performance and gradually declining costs. [29]

2.1.1.2 Suspended Particle Device (SPD) Glazing

- **Mechanism and Stimulus**

Suspended Particle Device (SPD) glazing uses a film of microscopic light-absorbing particles suspended in a fluid or polymer. In the unpowered state, the particles are randomly oriented, blocking light and making the glass appear dark. When ~ 100 V AC is applied, the particles align, allowing light to pass and rendering the glazing transparent. SPD is an active technology that requires continuous power to stay clear; once power is removed, the particles return to their random, darkened state. [35-38]

- **Switching Speed and Power**

SPD smart glass offers rapid switching, typically transitioning between clear and tinted states in 1–3 seconds, independent of glass size. This is significantly faster than electrochromic or thermochromic technologies, making it ideal for applications requiring quick glare control. SPD requires continuous power to maintain transparency, drawing a modest ~ 1.5 W/m² (comparable to an LED bulb). If power is lost, the glass defaults to its tinted state, which can act as a passive shading feature. [37, 38]

- **Appearance**

SPD glazing appears deep blue or gray in the off (dark) state and slightly tinted in the clear (on) state, with ~ 50 – 60% VLT when transparent. In its darkest state, it can block up to $\sim 99\%$ of incident light, offering excellent glare and heat control. Unlike PDLC, SPD maintains through-vision even when tinted, behaving like sunglasses rather than privacy glass. Modern SPD films have low haze (~ 2 – 3%), preserving clarity in both states. The tint is continuously adjustable via voltage for customized shading. [37]

2.1.1.3 Polymer-Dispersed Liquid Crystal (PDLC) Glazing

- **Mechanism and Stimulus**

Polymer-dispersed liquid crystal (PDLC) glazing consists of microscopic liquid crystal droplets embedded in a polymer film, laminated between glass panes. In the power-off state, the LC molecules are randomly oriented, scattering light and making the glass appear milky or translucent. When an AC voltage (typically 50–110 V) is applied, the droplets align, matching the refractive index of the polymer and allowing light to pass through, making the glass appear clear. PDLC is an active technology, requiring power to maintain transparency and reverting to privacy mode when off (**Figure 6**). [36, 37]



Figure 6: PDLC glazing in OFF and ON states [39]

- **Switching Speed and Power**

PDLC films switch extremely fast, typically within 10–100 milliseconds, appearing instantaneous to the human eye. The technology requires continuous power to stay clear, with power consumption around $< 2 \text{ W/m}^2$. When power is off, the glass defaults to its opaque (privacy) state. PDLC is primarily a binary system, clear or opaque, though limited intermediate diffusion is possible with partial voltages. [37]

2.1.1.4 Gasochromic Glazing

- **Mechanism and Stimulus**

Gasochromic glazing uses a reactive gas, typically hydrogen or oxygen, to alter the optical state of a tungsten oxide (WO_3) coated surface within a sealed glazing unit. Injecting hydrogen reduces the WO_3 , turning the glass blue-dark; introducing oxygen or air oxidizes it back to a clear state. The gases are supplied by a compact electrolyzer and operate in a closed loop, with minimal gas volumes. This is an active system, requiring pumps or valves but no electrical voltage applied directly to the glazing. [40, 41]

- **Switching Speed and Power**

Gasochromic glazing offers fast switching and a wide transmittance range. Coloration typically occurs within a few seconds to a couple of minutes, depending on gas flow rate and window size, which is often faster than electrochromic due to gas-phase diffusion, which bypasses slow ion movement in solid films. Water-infused WO_3 coatings enhance hydrogen transport and allow operation at higher temperatures. Well-optimized systems show uniform switching and impressive dynamic range: up to ~77% VLT when clear and ~6% when tinted. Even darker states are achievable with thicker coatings. Power consumption is minimal, used only to run a small electrolyzer or pump, making energy use comparable to or lower than electrochromic systems. [40]

- **Appearance**

Gasochromic glazing using tungsten oxide typically exhibits a blue-grey tint when darkened and a color-neutral appearance when clear. The transition is uniform and haze-free, maintaining good optical clarity. A slight residual tint may remain if the coating isn't perfectly neutral, but modern systems are designed for high transparency in the bleached state. Some gasochromic variants, such as switchable mirror windows using metal hydrides

(e.g., Mg–Ti alloys), can toggle between a clear and reflective mirror state. Standard gasochromic windows offer strong control over both visible and infrared transmittance, making them effective for combined daylight and solar heat management. [40]

2.1.2 Passive Smart Glazing Technologies

Passive smart glazing technologies operate autonomously, changing their properties in response to environmental conditions without any external control system or power input. They leverage inherent material responses to stimuli like temperature or sunlight. The main passive technologies in smart windows are thermochromic, thermotropic, and photochromic glazing [9, 31]. In these systems, the window adapts continuously to climate conditions, for example, darkening on a hot sunny afternoon and reverting on a cooler or cloudy day, essentially self-regulating. Each type of passive smart glazing is discussed below.

2.1.2.1 Thermochromic Glazing

- **Mechanism and Stimulus**

Thermochromic glazing changes its optical properties in response to heat, transitioning between transparent and tinted states without any electrical input. A common material, vanadium dioxide (VO_2), switches at around 68 °C (reduced to ~50–60 °C with doping) from a transparent semiconductor to a reflective, infrared-blocking state, reducing solar heat gain while maintaining visible light transmittance. Other systems use thermochromic interlayers (e.g., Suntuive® [42]) that gradually darken when warmed by sunlight. The effect is passive and reversible: tinting is triggered by solar heating and fades as the window cools. The Structure and working mechanism of electrochromic glazing is shown in *Figure 7*. [43, 44]

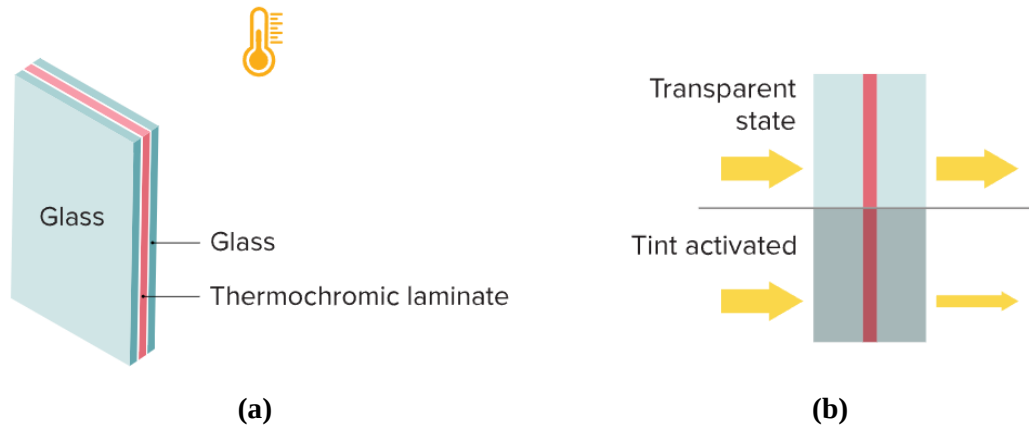


Figure 7: (a) Structure and (b) working mechanism of thermochromic glazing [33]

- **Switching Characteristics**

Thermochromic glazing responds gradually to temperature changes, with switching speed tied to how quickly the glass heats or cools, typically over several minutes. VO_2 coatings show a relatively sharp transition around 50–68 °C, while polymer-based systems (e.g., Suntuive) tint progressively over a broader range. Switching is passive, with no manual control; it follows environmental heat. Transmittance changes are moderate: polymer systems may vary from ~60% to ~20% VLT, while VO_2 coatings reduce infrared transmission significantly, with only minor visible light changes (e.g., 70% to 50% VLT), making them ideal for passive heat control without major loss of daylight. [42-44]

2.1.2.2 Thermotropic Glazing

- **Mechanism and Stimulus**

Thermotropic glazing changes from clear to translucent (light-scattering) in response to heat, without significant color change. This occurs via phase separation in a polymer or gel layer, forming microstructures that scatter light. Below the switching temperature, the material is uniform and transparent; above it, domains form that diffuse light, turning the glazing milky or opaque. Unlike thermochromics, the optical shift is transparency vs

opacity, not clear vs tinted, making thermotropics ideal for passive glare and privacy control. [45-47]

- **Performance**

Thermotropic glazing typically switches at 30–40 °C, aligning with sun-heated glass temperatures. The transition can be sharp or gradual, depending on the material formulation. Switching speed is tied to heat buildup and is often within 1–2 minutes under direct sunlight. These materials can reduce direct light transmittance from >80% to ~20%, diffusing or reflecting incoming solar radiation. Variants include scattering, reflective, and absorbing types, with scattering being most common. Products like SOLARDIM turn white and reflective above threshold temperatures. Optical hysteresis helps avoid rapid toggling near the switching point. [47, 48]

2.1.2.3 Photochromic Glazing

- **Mechanism and Stimulus**

Photochromic glazing darkens in response to sunlight, particularly UV radiation. The material contains photo-reactive compounds (e.g., silver halide crystals or organic molecules like spiropyrans) that change structure when exposed to UV, shifting to a tinted, light-absorbing form. When UV light fades, the compounds revert to their clear state. The process is fully passive, requiring no electrical power; sunlight alone triggers and reverses the tint (*Figure 8*). [49-51]

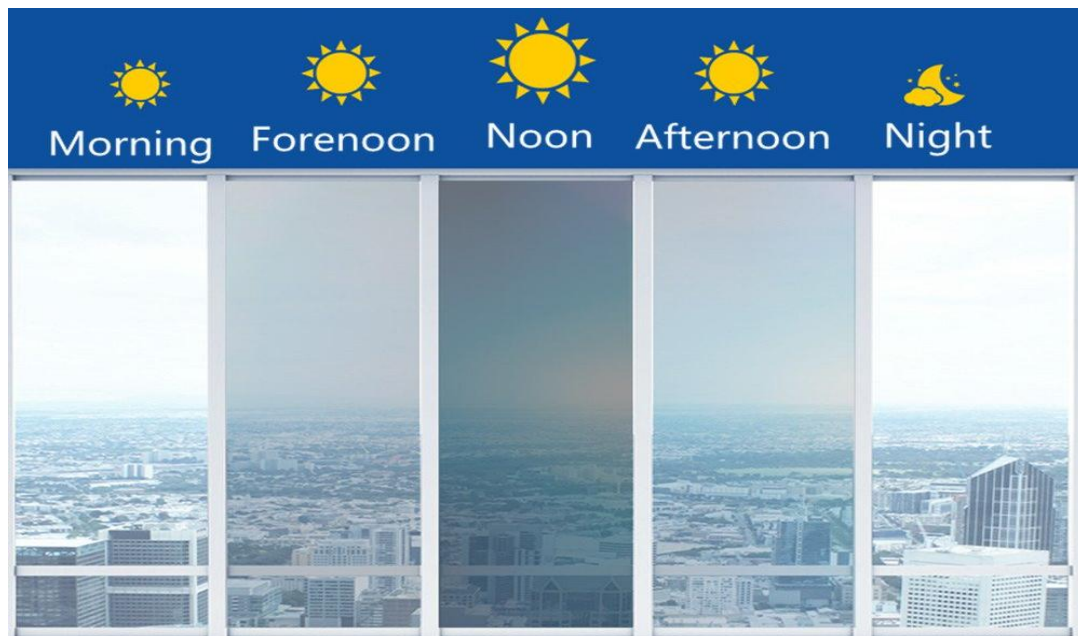


Figure 8: Photochromic glazing response to daylight conditions throughout the day [52]

- **Performance**

Photochromic glazing darkens within seconds to a minute under strong sunlight and lightens gradually over several minutes once UV exposure stops. It can shift from ~70% to ~20% visible transmittance (T_p), offering significant glare reduction. Unlike thermochromics, activation depends on UV intensity, not temperature, so tinting occurs even on cold sunny days. Some systems offer continuous tint modulation based on light levels. A key limitation is reduced activation when installed behind UV-blocking glass, though newer formulations respond to broader light spectra for improved performance in buildings. [50, 53]

2.1.3 Summary

In summary, smart glazing technologies offer dynamic control over window performance, either actively (with external triggers like electricity or gas) or passively (self-acting via environmental cues). Active systems such as electrochromic, SPD, PDLC, and

gasochromic windows allow controllable and often more extreme modulation of light/heat, at the expense of requiring power/control systems. Passive systems like thermochromic, thermotropic, and photochromic glazing provide self-adjusting behavior without power, offering simplicity and inherent response, but generally with no user override and somewhat less flexibility. Each technology has its niche strengths: for instance, electrochromic windows are now proven in building energy savings but have slower response; SPD is ultra-fast and effective for solar control but needs constant power and is costly; PDLC is great for privacy on demand but doesn't save energy; thermochromic/thermotropic work automatically to cut cooling loads but sacrifice some view; photochromic gives automatic glare control but could inconvenience if not desired at times.

2.2 Sustainability

Sustainability is a complex concept that has various definitions in literature. However, a widely accepted definition was provided by the United Nations in 1987, stating sustainability as “*meeting the needs of the present without compromising the ability of future generations to meet their own needs* [54]”. IBM refers to sustainability as the long-term goal of enabling humans to live on Earth without exhausting its natural resources, thereby ensuring a sustainable environment for both humanity and the planet [55]. In essence, sustainability in terms of products, processes, and systems refers to the ability of a system or process to continue functioning over time without depleting different types of resources. Generally, three pillars/dimensions of sustainability have been recognized in literature: environmental, social, and economic. Accordingly, achieving sustainability involves the development of projects that effectively balance these factors, ensuring they

do not compromise the immediate needs of the environment and society, nor those of future generations. [56].

Sustainability in construction involves planning, designing, constructing, operating, and managing buildings in a way that reduces their environmental footprint while enhancing their social and economic advantages. This approach employs eco-friendly and sustainable materials, energy-efficient systems, waste reduction practices, and healthy indoor environments, with the goals of conserving natural resources, reducing greenhouse gas emissions, and enhancing the well-being of occupants and the community. Smart materials are essential for enhancing sustainability, as they can sense and respond to environmental changes, offering dynamic solutions that improve energy efficiency. [57, 58].

2.2.1 Sustainability Assessment and Frameworks

Sustainability assessment is an intricate and comprehensive appraisal method that involves the identification, measurement, and evaluation of the potential impacts of different options concerning sustainability [59, 60]. Further, it is referred to as processes that “direct the planning and decision-making process toward achieving sustainable development.” [61]. More generally, Sustainability assessment refers to the process of systematically evaluating the environmental, social, and economic dimensions of sustainability performance for a product, technology, project, or organization over its lifecycle to aid decision-making and the formulation of policies within a wide-ranging context [60, 62]. The assessment of sustainability is progressively becoming a standard procedure in assessing products, policies, organizations, and specifically in the built environment for buildings. Currently, there's a range of tools and indicators of sustainability assessment designed for specific

purposes and levels of assessment, covering products, companies, industries, and broader societal evaluations are available [63].

2.2.2 Previous Research on Sustainability Assessment

In an effort towards the sustainability assessment for smart glazing technology, *Elkhayat, Y.O., et al.* [20] used the Life Cycle Assessment (LCA) tool to investigate and compare the total energy consumption and environmental impacts of three High-performance glazing systems with conventional Clear double-glazing systems from extraction to disposal. The results will help building designers and decision-makers choose the most environmentally friendly HPGS for their office buildings. *Moussavi Nadoushani, Z.S., et al.* [23] conducted a real case study focused on choosing a new facade for an existing building in Sydney. This study aimed to fill gaps in existing knowledge by emphasizing economic, environmental, and social factors when selecting sustainable facade systems. It presented a systematic method for choosing a facade system based on these sustainability criteria, examining how different criteria impact decision-making, and assessing their relative importance in practical applications. However, the study misses out on the glazing system or specifically the smart glazing systems for the evaluation.

Moghaddam, S.A., et al. [22] reviewed and analyzed various glazing systems in the context of achieving nearly zero-energy buildings (NZEBs) while focusing on four key aspects; Energy performance, Thermal comfort, Cost-effectiveness, and Environmental impacts. Hence, it presented a comprehensive review and an approach toward the glazing selection for NZEBs. While the study offers a thorough analysis of glazing systems for NZEBs, it does have some limitations. For instance, the study covered all types of established glazing technologies with a specific inclination towards NZEBs but did not fully capture the

advanced smart glazing technologies. Moreover, in its comprehensive approach, it lacks integrating a key occupants' comfort factor e.g., glare and visual comfort.

Some studies optimized the multi-criteria decision-making (MCDM) approach for weighing the criteria and the selection of optimal glazing or façade for buildings but still its application in façade selection is relatively new, especially for glazing systems. The frequently utilized MCDM methods in construction and building technology include WSM, WPM, AHP, TOPSIS, Choquet Integral, ELECTRE PROMETHEE, VIKOR, and MIVES [64-66]. For instance, *Elkhayat, Y.O., et al.*, [25] addressed the challenge of selecting the most sustainable High-performance glazing system for an office building in the hot desert climate of Egypt. For this purpose, this paper applied the MCDM approach using the Analytic Hierarchy Process (AHP) to rank three glazing options (Low-E, Electrochromic, and Photovoltaic glazing) based on four sustainability criteria (Energy, Environmental life-cycle assessment, Cost, Occupant Comfort-Thermal and Visual comfort). However, this study is applied to a specific building type (Office building) and climate (Egypt). Further, it lacks in comprehensively assessing all the intelligent glazing. *Balali, A. and A. Valipour* [19] conducted a study that focused on identifying and prioritizing the most suitable building façade's smart materials thereby proposing a framework for selecting smart materials for building facades based on their contribution to sustainable development goals (SDGs). This study optimized the MCDM technique to weigh the importance of different SDGs and prioritize the materials based on their overall sustainability contribution. Hence, the study found that photovoltaic, thermochromic, and photostrictive materials are the most promising choices for sustainable building facades. However, this study focuses on the contribution of materials to SDGs but doesn't delve deeply into their life cycle assessment or cost-effectiveness. A comprehensive evaluation

of the environmental impact and economic viability of these materials throughout their life cycle is crucial for informed decision-making. Furthermore, this study was conducted for the climatic condition of Shiraz, Iran so the framework might not apply to other locations. The thermal and optical properties of a glazing system (i.e., the U-value and g-value) are significantly influenced by factors such as local climatic conditions. Habibi, S., et al. [21] presented a comprehensive assessment model combining MIVES (Multi-criteria Interactive Visual Exploration System) and Delphi for evaluating the sustainability of intelligent façade layers (IFLs) in educational building renovations. Further, it validated the model with five IFL alternatives (A1- ETFE inflating cushion, A2- Bioreactor panels, A3-Ever-changing PC, A4- Kinetic PTFE Mashrabiya layer, A5-TiO₂ covered thermoformed tiles) and three case studies in Barcelona schools. However, this assessment model is mainly focused on some specific aspects like energy savings and occupant comfort, neglecting broader sustainability considerations like environmental impact and cost-effectiveness. Further, it focused solely on educational buildings, specifically schools with the specific climate of Barcelona. Lastly, the study didn't consider any intelligent glazing for IFLs.

Hence, different types of intelligent glazing have been extensively researched and studied, from an innovative technology perspective, structural composition, energy efficiency/energy simulations, thermal comfort evaluation, daylight, and visual comfort assessment following their manufacturing, performance, application, potentials, and drawbacks. Moreover, the literature suggests a hypothesis that utilizing smart glass within building structures can potentially offer optimal solutions for adapting buildings to varying climatic and environmental conditions. This adaptation aims to enhance the thermal comfort of occupants while also aligning with the Sustainable Development Goals (SDGs).

These SDGs encompass the improvement of health standards, addressing the challenges of climate change, and enhancing the overall sustainability of buildings.

However, there are several limitations. For instance, while some studies employ life cycle assessments and multi-criteria decision-making methods to evaluate glazing systems, they often focus on specific climates or building types, thereby restricting the broader applicability of their findings. Further, the mentioned studies related to glazing were studied either generally for the sustainability assessment and selection of glazing systems or limited high-performance glazing systems thereby highlighting the potential for the sustainability assessment of smart glazing technologies specifically. Following this, these assessments lack comprehensive coverage of all smart glazing options available, leading to potential oversight of emerging technologies. The absence of in-depth evaluations considering the full life cycle, economic, and technical assessment of smart glazing materials used in facade systems remains a notable gap, hence, restricting the informed decision-making for the selection of sustainable smart glazing material. Additionally, studies focused solely on specific sustainability dimensions, such as energy savings or occupant comfort, may overlook other crucial aspects, limiting the holistic assessment of smart glazing technologies. Consequently, the existing studies, while informative, face limitations in scope, applicability, and the comprehensive evaluation of all available smart glazing solutions across diverse environmental, economic, and technical contexts.

2.2.3 Sustainability Potential of Smart Glazing

Smart glazing technology exhibits significant advantages for buildings towards all the pillars of sustainability as compared to conventional glazing systems [67]. *Taher, R., et al.*, hypothesized that smart glass, integrated into the building envelope, functions as a climate-

adaptive building shell, offering potential solutions to optimize buildings in response to diverse climatic and environmental conditions [14]. This adaptation improves users' thermal comfort and visual comfort, reduces the need for mechanical cooling and heating systems, lowers energy consumption, enhances daylight availability, and minimizes negative environmental impacts, while significantly contributing to the achievement of Sustainable Development Goals (SDGs), such as improving health, addressing climate change, and promoting responsible energy consumption [14].

Several studies have explored the different benefits and performance elements of smart glazing that contribute to the sustainability of buildings as compared to conventional glazing systems. For instance, studies have been conducted to assess the thermal, visual, and energy performance of smart glazing in different climatic conditions for various types of buildings. For instance, *Taher, R., et al.* [14] investigated the potential of smart glass technology to improve thermal comfort and energy efficiency in highly glazed buildings, particularly in sunny locations like Cairo, Egypt. The study compared the thermal performance and cooling loads of the building with various types of smart glass, like thermochromic, electrochromic, and Low-E glazing by simulating a highly glazed office building using Design Builder software. The results indicated that smart glass significantly improves thermal comfort, reduces energy consumption, maintains daylighting, and somehow enhances aesthetics thereby offering sustainable and energy-efficient solutions for achieving thermal comfort in highly glazed buildings. More specifically focusing on using smart glass technology, the study concluded that Electrochromic glazing showed the best thermal performance, reducing operative temperatures by 3–7 °C. However, Thermochromic glazing had the least impact as it reduced the operative temperatures by 2–5 °C. For energy consumption, using split air-conditioning units with these solutions cut

cooling energy consumption by 21–36.4%. Thermochromic glazing led with 36.4% savings, while electrochromic, despite better thermal performance, achieved 21% due to its electricity usage. *Hemaida, A., et al.* [15] conducted a study that study focused on the analysis of PDLC (Polymer Dispersed Liquid Crystal) glazing for its thermal and optical properties in the context of enhancing building energy efficiency and occupant comfort. The optical properties were measured using spectrophotometry, revealing its solar transmittance and reflectance across varying wavelengths (UV to NIR), While the thermal performance was evaluated through Solar Heat Gain Coefficient (SHGC) and U-value measurements in both translucent and transparent states. According to the results, the PDLC system provides variable transparency, with solar modulation for transparent and translucent states varying from 62% to 42%, respectively. It has shown low transmissions of UV (8–14%) and Near Infrared (NIR) (37–44%), suggesting the possibility of UV protection. The PDLC glazing showed efficient heat reduction in terms of thermal behavior, as evidenced by SHGC values of 0.68 (transparent) and 0.63 (translucent). It was observed, nevertheless, that the hotter internal glass surface might produce secondary heat and make occupants uncomfortable. Overall, the PDLC glazing system exhibits promise for energy-efficient buildings by regulating solar heat gain and offering UV protection while allowing variable transparency. However, attention is needed to mitigate potential secondary heat gain issues for occupant comfort. *Shaik, S., et al.* [68] conducted both numerical simulations and laboratory investigations to analyze the optical characteristics of different smart PDLC film glasses (white, blue, pink, and yellow). Their findings indicated that the white smart PDLC film exhibited the highest energy efficiency among these variations, resulting in the most substantial annual savings in air-conditioning costs.

For visual comfort coupled with energy efficiency, *Cannavale, A., et al.* [16] comprehensively reviewed and explored the potential benefits of integrating Electrochromic glass in building facades, focusing on energy savings and visual comfort. Further, the study also emphasizes EC glass structure, control strategies, and climatic influences on energy consumption and visual comfort while highlighting some challenges like high initial cost. Three electrochromic devices' luminous characteristics were investigated by *Piccolo, A., et al.* [18] to determine how they might improve energy efficiency and visual comfort. The study showed that there is a trade-off between energy efficiency and visual comfort in smart windows and that focusing too much on one could have negative effects on the other. For instance, different control strategies for electrochromic windows led to varying impacts on energy reductions and indoor comfort levels, showcasing the challenge of balancing these objectives simultaneously. *Mesloub, A., et al.* [69] using Energy Plus simulations, discovered that SPD smart glass, when in the off state or controlled for radiance, achieved energy savings of up to 58% compared to double glass low-E, particularly in South, East, or West orientations. However, this improvement negatively impacted on lighting and visual comfort.

The potential of smart glazing for saving energy in the building sector has been extensively investigated using simulation software. Smart glazing technologies significantly reduce energy consumption in buildings, which is a key objective in achieving sustainability. Electrochromic (EC) smart glazing, for instance, in its highest state, holds the ability to obstruct up to 90% of solar radiation, resulting in a substantial decrease in the transmission of energy from the exterior to the interior. This capability allows EC glass to lower peak energy loads by 23% to 30%, resulting in a 20% reduction in overall energy consumption and decreasing the required size of the HVAC system needed to efficiently service the

building. [70]. *Aburas, M., et al.* [71] using a systematic review drawn from architecture and engineering databases, researchers determined that Thermochromic glazing possesses the capacity to reduce heating and cooling energy demand by 5% to 84.7% compared to regular glass, contingent on climatic variations and the specific glazing utilized. Additionally, they observed considerable divergence in energy efficiency across various cities employing the same type of film. However, the differences in energy performance were less pronounced when comparing different film types within the same city. It enhances the energy efficiency of buildings, particularly in warmer climates and especially in structures with extensive glass surfaces (highly glazed buildings) [72, 73]. In essence, Smart windows are also essential for reducing carbon emissions in the building sector. By integrating smart glazing in a building's envelope, the energy consumption of a building can be greatly reduced, transforming an energy-intensive structure into a low-energy or less energy-demanding one. [67]

Moreover, Smart glazing optimizes occupants' comfort by enhancing indoor thermal conditions and enabling precise management of daylight levels and glare for better visual comfort [54]. Primarily, it controls the sunlight/heat entering the indoor space with comfortable daylight [41]. In terms of cost savings, smart glazing can autonomously control light transmittance, eliminating the need for shading devices, blinds, and louvers, along with the associated capital costs [74]. Overall, smart glazing technologies exemplify how advanced building components can support all sustainability pillars. However, to fully capitalize on these benefits, one must carefully evaluate which smart glazing option is most suitable for a given building context, a process that calls for a robust sustainability assessment framework.

2.2.4 Smart Glazing in Hot Climate: Potential and Sustainability for Non-Domestic Buildings

The built environment is greatly influenced by the selection of building materials, especially in areas with challenging climates like Saudi Arabia, with its harsh temperatures. The optimum choice of materials affects a building's long-term sustainability in addition to determining its functional and aesthetic aspects. In the challenging hot climate, building materials must exhibit resilience against extreme heat and other environmental stressors, while simultaneously fulfilling the functional requirements of the building's design. Collectively, the properties of these building materials contribute to the overall "sustainability of the building," a concept that might fluctuate significantly across different climates and regions. In essence, Sustainable building is a multi-faceted approach that aims to design and create buildings that are environmentally responsible, economically viable, and socially beneficial. [58]. Moreover, buildings are widely acknowledged as a significant contributor to global warming, accounting for 40% of global energy consumption and 30% of carbon emissions. Buildings consume energy primarily for lighting, heating, and cooling, which emphasizes the need for energy-efficient and sustainable solutions in this industry [75, 76]. Currently, space cooling represents about 20% of the energy used in buildings worldwide and contributes 8% to the total carbon emissions from energy consumption [77]. By 2050, the number of air conditioning units in use is expected to surge to 1,194 million, up from 292 million in 2020, driven by high demand in hot climates [76]. This increase will likely triple the global energy demand for space cooling, rising from around 2,000 TWh today to 6,000 TWh [77].

To address these challenges and to achieve sustainability objectives, the optimal selection of smart and sustainable materials must be done [58]. One such innovative building

material is smart glazing, which can significantly improve energy efficiency by reducing the need for artificial heating and especially cooling demand in hot climatic regions, enhances occupant comfort by optimizing natural light and reducing glare, reduces the environmental footprint by reducing carbon emissions, and enhances the energy efficiency thereby enhancing the overall sustainability of the building, aligning with LEED standards [78]. According to the National Renewable Energy Laboratory (NREL), EC glazing can lower electricity consumption by up to 49% while also saving up to 51% on lighting costs. The high level of energy efficiency has increased the demand for electrochromic glass in non-domestic buildings. [79]

2.2.4.1 Adoption and Growth Projections

The global smart glazing market is quickly expanding, owing to the growing emphasis on energy efficiency and sustainability within the building industry and increasing initiatives aimed at technological innovations, followed by smart and sustainable buildings [79, 80]. According to **Markets and Markets** report, the global smart glass market, valued at \$5.4 billion in 2023, is expected to reach \$9.4 billion by the end of 2029, with a compound annual growth rate (CAGR) of 9.8% [81]. However, the **Grand View Research** report states the global smart glass market at \$6.59 billion in 2023 and is estimated to grow at a CAGR of 9.9% from 2023 to 2030 [79]. **Figure 9** depicts a regional overview of the smart glass market's growth, highlighting Europe's dominance, which is driven by infrastructure renovations. Energy efficiency demands drive North America's rise, whilst Asia Pacific is experiencing a spike due to industrialization and construction. The Middle East is likewise quickly adopting technology, driven by economic growth and infrastructure development [82]. Moreover, in the building sector, Smart glass is most commonly employed in

commercial office buildings and corporate headquarters since it helps to reduce costs while enhancing workplace efficiency [82, 83].

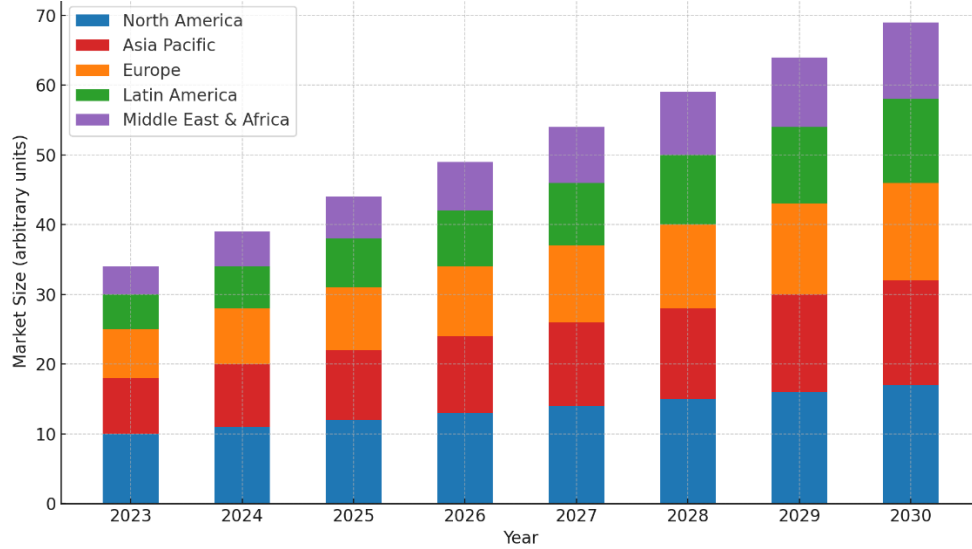


Figure 9: Projected growth of the smart glass market in different regions (2023-2030) [82]

Notably, the Middle East, with its hot climate and burgeoning construction industry, presents a significant opportunity for smart glazing adoption. The market is expanding because of rising investments in smart infrastructure and development, especially in the luxury, non-domestic, and commercial buildings. In the upcoming years, it is anticipated that the market will develop significantly due to technological advancements and the growing desire for sustainable solutions. [83].

2.3 Sustainable Smart Glazing System Selection Using MCDM

In multi-criteria decision-making (MCDM) problems such as the sustainable smart glazing selection in this study, determining appropriate weights for each evaluation criterion is a crucial step. Criteria weighting methods generally fall into two categories: subjective and objective. [84] As discussed further in the following sections.

2.3.1 Subjective Weighting (Likert Scale Approach)

Subjective weighting in MCDM refers to assigning importance weights to criteria based on human judgment and is influenced by experience, priorities, or specific decision-making contexts rather than data-driven calculations [85]. In this approach, experts or stakeholders directly express their preferences for each criterion. A common technique is using a Likert scale survey – for example, rating each criterion on a scale (e.g., 1 to 5 or 1 to 7) from least to most important. These ratings capture perceived importance in a straightforward, quantitative way. Likert-based weighting is intuitive and easy to implement. Moreover, decision-makers find such rating scales simple and familiar, which encourages participation and honest input [86]. The aggregated ratings can then be translated into weights by appropriate normalization.

Using a Likert scale is particularly useful for determining high-level priorities (such as main criteria or sustainability dimensions) because it incorporates stakeholders' or experts' insight into what matters most. It allows flexibility to emphasize strategic criteria that might not be evident from raw data alone [85, 86]. For instance, in sustainable glazing selection, experts might strongly rate energy efficiency as “very important” relative to cost or technical criteria, reflecting organizational sustainability goals. These subjective weights ensure the MCDM model aligns with the value-driven preferences of the decision-makers.

However, one must be cautious of the limitations of subjective weighting via Likert scales. The input is inherently biased by personal judgment and experience. Different respondents may weigh criteria inconsistently or with various interpretations. The Likert ratings are ordinal and coarse, which can introduce bias or reduce precision in the derived weights [86]. For example, respondents might avoid using the extreme ends of the scale (central

tendency bias) or might give high ratings to many criteria (positivity bias), skewing the results. Consequently, the quality of subjective weights depends on having knowledgeable, representative respondents and careful survey design. Despite these caveats, the Likert scale approach remains a practical method to obtain criterion weights that reflect human priorities in an MCDM problem.

2.3.2 Shannon Entropy Method for Objective Weighting

In contrast to subjective methods, objective weighting derives criteria weights from the dataset itself, without direct human bias [85]. One widely used objective technique is the Shannon entropy method. The core idea of entropy weighting is to measure the amount of information or uncertainty in the performance values of each criterion across the alternatives. Criteria that exhibit greater variability or dispersion in their values contain more information (lower entropy), and thus are assigned higher weight, whereas criteria with uniform values (higher entropy) are given lower weight [87]. In other words, the more a criterion distinguishes between the alternatives, the more important it is considered [88]. This aligns with the logic that a criterion that shows significant differences in outcomes has a larger impact on the decision.

The Shannon entropy method provides an unbiased, data-driven way to determine weights. It is especially suited for cases where criteria are evaluated through measured or simulated data rather than subjective opinions. For example, in a smart glazing selection study, objective performance metrics can be compiled for each glazing option. The entropy method will calculate weights for these metrics based solely on their variations in the data, without any expert influence. An attractive feature of this approach is that it **avoids subjective bias** entirely. The weights reflect only what the data indicates about criterion

significance. Moreover, using entropy weighting is appropriate for simulation-based or literature-derived data (i.e., “non-opinionated” data) because it treats the dataset as the source of truth for criteria importance. [88]

2.3.3 TOPSIS

The Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) is a classical multi-criteria decision-making (MCDM) method introduced by Hwang and Yoon in 1981. It ranks decision alternatives by comparing their distances to two hypothetical reference points: an ideal solution and a negative-ideal solution. The ideal solution represents the best attainable performance in all criteria (e.g., maximum benefits and minimum costs for each factor), whereas the negative ideal (anti-ideal) solution has the worst values on all criteria. In practice, the optimal choice is the alternative closest to the ideal solution and farthest from the negative-ideal in the multi-dimensional criteria space. [89]

TOPSIS employs a geometric distance approach to quantify these comparisons. Specifically, each alternative’s performance is evaluated by calculating its Euclidean distance from the ideal point and the worst point. This yields a couple of distance measures for every option. From these, a *relative closeness* index is computed to facilitate ranking: typically defined as the ratio of an alternative’s distance from the negative-ideal to the sum of its distances from both ideal and negative-ideal. The closeness value ranges from 0 to 1, with a value closer to 1 indicating that the alternative is relatively nearer to the ideal solution (and thus preferable). Finally, alternatives are ranked in descending order of this closeness coefficient, so that the option with the highest relative closeness to the ideal is chosen as the best among the set. [90, 91]

Hence, this process ensures the ranking accounts for both how well an alternative performs on each criterion *and* how it balances trade-offs between the best and worst possible outcomes on those criteria.

In terms of sustainability relevance, TOPSIS has become a popular tool for sustainability evaluations and other MCDM applications owing to its intuitive logic and practical advantages. Studies across various fields report that TOPSIS (often alongside AHP) is among the most widely used decision-making techniques for assessing sustainability criteria [92, 93]. The method's appeal lies in its simplicity and clarity: TOPSIS involves relatively straightforward computations and has a transparent rationale that decision-makers find easy to understand [94]. Unlike more complex MCDM methods, it does not require intensive pairwise comparisons or iterative solvers – instead, it directly uses the performance data and weights to produce a ranking, which keeps the analysis efficient even as the number of criteria or alternatives grows. Researchers note that TOPSIS can be readily applied to problems with a large number of evaluation criteria and options, with few computational difficulties. [94]

Hence, this efficiency, combined with the method's clear geometric interpretation (distance to an ideal point), makes it well-suited for sustainability decision contexts where multiple performance metrics (economic, environmental, social, etc.) must be balanced. Moreover, TOPSIS's consideration of both an ideal and a worst-case solution aligns with the way human decision-makers intuitively consider the best and worst outcomes, helping to ensure the chosen solution is not only excellent in some respects but also acceptable across all criteria. These characteristics have led to TOPSIS being widely adopted in green building assessments, energy technology selections, and other sustainability-related MCDM problems that require robust yet user-friendly evaluation tools.

2.3.4 Normalization Techniques in MCDM

In multi-criteria decision-making (MCDM), criteria often have different units or scales, so their raw values must be normalized into a comparable range before analysis [95]. Normalization produces a dimensionless **decision matrix** that allows fair weighting and aggregation of criteria. This is especially crucial for methods like the *entropy weight method (EWM)*, which objectively determines criterion weights based on the dispersion of values in the decision matrix. In entropy weighting, normalization can influence the calculated weights by altering the distribution of criterion values[96]. Key considerations for choosing a normalization method include:

- **Handling benefit vs. cost criteria:** Ensuring the method can adjust cost-type criteria into benefit-oriented normalized values.
- **Scale invariance:** Insensitivity to the units or magnitude of measurement (i.e., changing units or multiplying all values by a constant doesn't affect the normalized outcomes).
- **Sensitivity to performance variability:** How the normalization method responds to significant differences in data magnitude across alternatives.
- **Interpretability:** How easily decision-makers can understand the meaning of normalized scores (e.g., 0 to 1 scale with clear reference points).

The most common normalization methods are Min–Max normalization, Max normalization, and Vector normalization [97]. Each normalization scales criteria values differently, affecting the computed entropy weights and thus the decision outcome. Below is a brief comparison of the mentioned normalization techniques to guide the choice of normalization technique based on decision matrix characteristics and study objectives.

2.3.4.1 Min–Max Normalization

It transforms each criterion value to a 0–1 range by subtracting the minimum and dividing by the range (max–min). For benefit criteria (where higher is better), the formula sets the minimum to 0 and maximum to 1; for cost criteria (where lower is better), the formula is inverted (max value yields 0). [98]

This linear scaling preserves the rank order and proportional differences of the original data, mapping the worst performance to 0 and the best to 1 for intuitive interpretation. However, because it relies on extreme values, Min–Max normalization is highly sensitive to large variations in data; a single extremely high or low value can disproportionately influence the scale, compressing the majority of other scores toward 0 and potentially biasing the resulting weights. [95]

2.3.4.2 Max (Maximization) Normalization

It scales values by the maximum value of each criterion. For a benefit criterion, each value is divided by the max (so the best becomes 1.0); for a cost criterion, one common approach is to use the minimum or an inverted form (e.g. using $\min/\text{value}$ or $1 - (\text{value}/\text{max})$ to ensure the lowest cost maps to 1). [99]

Max normalization is simple and, like Min–Max, it produces dimensionless ratios independent of units. It does not force the worst value to zero unless a true zero is present, which means moderate performances aren't overly flattened. Nonetheless, this method is still dependent on the maximum value within a criterion. A significantly higher value can diminish the relative scale of other alternatives, though the effect is typically less pronounced than in Min–Max normalization, which forcibly stretches values across the full

0–1 range. The normalized scores are interpretable as a percentage of the best performer (e.g., 0.8 means an alternative is at 80% of the top value for that criterion).

2.3.4.3 Sum Normalization

It converts each criterion's values into fractions of the total by dividing each value by the sum of all values for that criterion. This method naturally yields *relative weights* or probabilities for each alternative on a given criterion (all normalized scores sum to 1.0). For cost criteria, a typical adjustment is to use the reciprocal of the value ($1/\text{value}$) or other inversion before dividing, so that smaller (better) costs result in larger normalized shares [100].

Sum normalization is scale-invariant under multiplication (changes of units) and preserves the proportionate relationships of the original data – each alternative's share of the total remains the same regardless of the absolute scale. Like the above methods, it can be skewed by extreme value disparities; a particularly large value may dominate the total sum, resulting in a normalized score close to 1.0 for one alternative, while others are reduced to near-zero values. The interpretability of sum-normalized values is moderate: they can be viewed as the percentage contribution of each alternative to the total criterion performance, which is mathematically convenient (especially for entropy calculations treating these as probability distributions) but less intuitive for stakeholders to interpret directly.

2.3.4.4 Vector Normalization

Scales values by the Euclidean norm (square root of the sum of squares) of each criterion's column. For benefit criteria, each value x_{ij} is divided by $\sqrt{\sum_i x_{ij}^2}$. For a cost criterion, one

approach is to normalize and then subtract from 1 (so that lower costs get higher scores).[100]

Vector normalization is the classic method used in TOPSIS and similar techniques because it accounts for the magnitude of all entries. It produces dimensionless values typically in the range $[0,1]$, but unlike Min–Max, it doesn't automatically pin the minimum to 0 or maximum to 1 unless those extremes dominate the vector. This method is invariant to the scale of measurement (e.g., multiplying all values by a constant leaves normalized ratios unchanged) and tends to preserve the *distribution* pattern of the original data. [95]

In other words, it avoids distorting the relative differences among alternatives – a feature that contributes to stable weight calculations. Vector normalization is somewhat less sensitive to extreme value variation, as it distributes the influence of large values across the entire norm of the criterion. The downside is that the normalized figures are less immediately interpretable (they represent a value's magnitude relative to the vector length, not a direct percentage of a best or total), which is usually acceptable for analytical purposes.

2.3.4.5 Summary

Table 1 provides a comparative analysis of all assessed normalization techniques for the entropy method. In summary, Min–Max and Max normalization are straightforward and yield bounded scores that are easy to explain, but they depend heavily on extreme values. Min–Max normalization, in particular, can exaggerate small differences by stretching the entire data range across the 0–1 scale, even when actual variance is minimal. It is also prone to instability when one or more values differ substantially from the rest, as these values disproportionately influence the scaling [95]. Sum and Vector normalization are more

robust in preserving the intrinsic distribution of data (important for objective weight computations) and avoid artificially stretching/compressing scores beyond the necessary scaling. Sum normalization conveniently provides a probability-like distribution for each criterion, directly aligning with the entropy weight formula. However, it can still be influenced by large value disparities within a criterion, leading to one alternative to dominate the distribution. Additionally, it does not constrain values to a fixed 0–1 range, which can limit interpretability. Vector normalization offers a balance by not overly distorting relative distances – studies have noted that it retains the original data patterns better than Min–Max and often yields more consistent weighting outcomes [95, 101]. The trade-off is that vector-normalized figures are not inherently intuitive without explanation.

Table 1: Comparison of normalization methods

Method	Benefit vs. Cost	Influence of High-Variance Data	Interpretability
Min–Max	$r_{ij} = \frac{x_{ij} - \min_j(x_{ij})}{\max_j(x_{ij}) - \min_j(x_{ij})}$ $r_{ij} = \frac{\max_j(x_{ij}) - x_{ij}}{\max_j(x_{ij}) - \min_j(x_{ij})}$	High: Extreme min or max values dictate the 0–1 range	High: Easy to understand (0 = worst, 1 = best for each criterion)
Max	$r_{ij} = \frac{x_{ij}}{\max_j(x_{ij})}$ $r_{ij} = 1 - \frac{x_{ij}}{\max_j(x_{ij})}$	Moderate: Relies on the single max; a very large max skews others downward.	Moderate: Scores indicate performance relative to the best (e.g., 0.8 = 80% of best)
Sum	$r_{ij} = \frac{x_{ij}}{\sum_{i=1}^m x_{ij}}$ $r_{ij} = \frac{\frac{1}{x_{ij}}}{\sum_{i=1}^m \frac{1}{x_{ij}}}$	High: One very large value can take nearly the entire share (close to 1.0), leaving others ~0.	Moderate/Low: Yields a proportion of the total (useful for calculations as probabilities) but not as intuitive for direct comparison by non-experts.
Vector	$r_{ij} = \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$ $r_{ij} = 1 - \frac{x_{ij}}{\sqrt{\sum_{i=1}^m x_{ij}^2}}$	Moderate: An extreme value influences the normalization factor (norm) and thus all scores, but overall, it maintains consistency in ranking	Low: Less transparent to stakeholders (values are based on geometric mean scaling), though suitable for mathematical accuracy.

CHAPTER 3

METHODOLOGY

The selection of sustainable smart glazing systems for non-domestic buildings in hot climatic regions demands a rigorous and context-sensitive evaluation process. This process must integrate diverse performance dimensions, including energy efficiency, visual and thermal comfort, economic feasibility, and technological viability. Although smart glazing technologies are gaining traction, a significant gap remains in structured, multi-criteria frameworks tailored to their sustainability assessment in hot climates. To address this gap, this study adopts a comprehensive and interdisciplinary methodological approach that combines systematic literature review, expert consultation, building performance simulations, and multi-criteria decision-making (MCDM) techniques. The methodology ensures scientific rigor, transparency, and practical applicability, culminating in the development and validation of a Sustainability Assessment Framework (SG-SAF) for smart glazing technologies. The detailed methodological steps are outlined in the subsequent sections, beginning with an overview of the full research design and flow.

3.1 Overview of Methodological Approach

The selection of sustainable smart glazing systems for non-domestic buildings in hot climatic regions necessitates a rigorous, multi-dimensional evaluation process. This process must account not only for energy performance but also for visual and thermal comfort, cost-effectiveness, and technological feasibility. Despite the increasing adoption of smart glazing technologies, a clear research gap exists in the form of structured, context-specific frameworks that assess their sustainability across multiple dimensions.

To address this gap, this study developed a comprehensive and robust Sustainability Assessment Framework for Smart Glazing (SG-SAF), specifically tailored for hot-climate office buildings. The methodology adopted is interdisciplinary and iterative, integrating systematic literature review, expert consultation, building performance simulation, and Multi-Criteria Decision-Making (MCDM) techniques. These methods were carefully selected to ensure scientific rigor, objectivity, and real-world applicability.

The research was structured around the following methodological steps:

- **S1 – Identification of Research Gap and Objectives**

A comprehensive literature review was conducted to examine existing sustainability frameworks and smart glazing applications. This review revealed critical gaps in current approaches and informed the definition of research objectives and questions.

- **S2 – Identification of Smart Glazing Alternatives and Initial Criteria**

A systematic literature review (SLR) was carried out to identify and compile potential sustainability criteria and smart glazing types relevant to non-domestic buildings in hot climates.

- **S3 – Curation and Categorization of Criteria**

Redundant and irrelevant criteria were eliminated, and the remaining set was categorized under four sustainability dimensions: Environmental, Social, Economic, and Technical.

- **S4 – Criteria Analysis**

Each sub-criterion was analyzed in terms of its definition, data type (quantitative or qualitative), optimal values, sustainability impact (direct or indirect), and its expected contribution to overall decision-making.

- **S5 – Validation and Prioritization of Criteria via Expert Survey**

A structured Likert-scale questionnaire was distributed to domain experts from academia and industry. Expert input was used to validate the relevance and importance of each criterion.

- **S6 – Expert Survey Results Analysis**

The survey data were analyzed using statistical techniques, including the Relative Importance Index (RII) and the Coefficient of Variation (CV), to finalize the hierarchy of criteria.

- **S7 – Data Collection for the Decision Matrix**

A case study of a real non-domestic building in a hot climate was selected for simulation in DesignBuilder. Performance data (thermal, lighting, energy use) were collected through calibrated simulation, while technical and economic data were sourced from literature, manufacturer datasheets, and supplier inputs.

- **S8 – Normalization of Decision Matrix**

The collected performance values were normalized using vector-based methods to enable cross-criterion comparability.

- **S9 – Weight Calculation**

A dual-weighting approach was adopted. Shannon Entropy was used to derive objective weights for sub-criteria, while subjective weights for main criteria were obtained from expert input.

- **S10 – Application of MCDM Method**

The TOPSIS (Technique for Order Preference by Similarity to Ideal Solution) method was applied to evaluate and rank the smart glazing alternatives based on their sustainability performance.

- **S11 – Framework Validation**

SG-SAF was validated through a multi-tiered process involving: (1) expert-driven validation of the criteria, (2) performance verification using a calibrated energy model, and (3) consistency of the weighting and MCDM methods. This ensured credibility, robustness, and practical applicability of the framework.

Figure 10 Illustrates the sequential flow of the research methodology, encompassing the eleven structured stages from gap identification to final validation of the SG-SAF. To complement this flowchart, *Table 2* provides a concise summary of how each research objective aligns with its corresponding questions, methodological approach, analysis techniques, and expected outcomes.

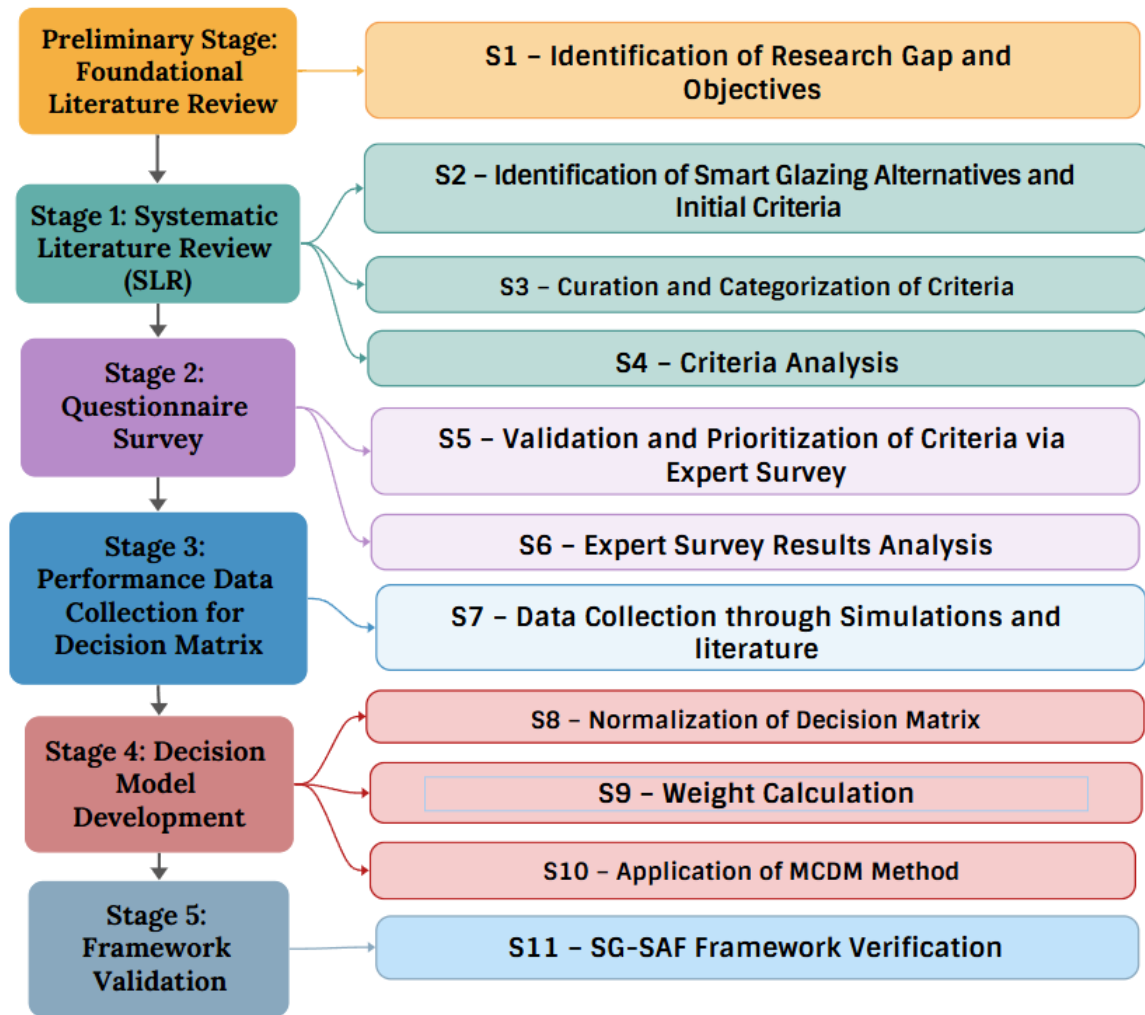


Figure 10: Methodological flowchart

Table 2: Research objectives, questions, methods, and expected outcomes

Research Objective	Research Questions	Research Method	Analysis Technique	Purpose/Expected Outcome
1. To critically review existing sustainability assessment frameworks and decision-making methods for smart glazing technologies, identifying gaps and limitations.	—	Preliminary Literature Review	- Thematic Synthesis - Gap Analysis	Define study focus and justify need by identifying gaps in current frameworks.
2. To systematically identify, categorize, analyze, and synthesize sustainability assessment criteria for smart glazing technologies, ensuring a comprehensive evaluation of environmental, economic, technical, and social dimensions tailored to sustainable building applications.	- What are the key sustainability criteria for assessing smart glazing in non-domestic buildings in hot climatic regions? - How can these criteria be systematically categorized and weighted for an effective decision-making framework?	Systematic Literature Review (SLR)	- PRISMA guidelines - Data Extraction and Synthesis - Content Analysis	Develop a comprehensive, structured, and validated set of sustainability criteria for smart glazing assessment.
3. To validate and prioritize sustainability criteria through expert consultation and statistical analysis, establishing a structured hierarchy that enhances decision-making effectiveness.	How do expert perspectives and statistical analyses contribute to validating and prioritizing sustainability criteria for smart glazing evaluation?	Questionnaire Survey (Likert scale)	Statistical Analysis (RII, CV, Descriptive Statistics)	Create a validated and prioritized hierarchical structure of sustainability criteria, enhancing decision-making effectiveness.

Research Objective	Research Questions	Research Method	Analysis Technique	Purpose/Expected Outcome
4. To develop and implement a Multi-Criteria Decision-Making (MCDM) framework (SG-SAF) for systematically assessing and ranking smart glazing technologies based on sustainability performance indicators.	- How can a Multi-Criteria Decision-Making (MCDM) framework be structured to systematically integrate quantitative and qualitative sustainability indicators for smart glazing technologies? - How can the proposed SG-SAF be implemented to rank and select smart glazing alternatives based on sustainability performance?	- MCDM Model (SG-SAF) - Objective & Subjective Weighting - TOPSIS Ranking	- Shannon Entropy - Normalized mean aggregation method - Vector Normalization - TOPSIS Analysis	Establish a robust, practical, and structured SG-SAF framework for assessing and ranking smart glazing technologies based on comprehensive sustainability indicators.
5. To verify the SG-SAF framework by ensuring internal consistency and alignment with established sustainability principles, preparing it for future validation	How effective and applicable is the SG-SAF framework in real-world decision-making processes for sustainable buildings?	- Validation through Expert Input - Case Study Simulation	- Comparative Analysis - Statistical validation (ASHRAE guidelines) - Expert survey Integration	Confirm the practical feasibility and reliability of the SG-SAF in real-world applications

3.2 Systematic Literature Review: Identification of Criteria

A Systematic Literature Review (SLR) is a structured research method that systematically identifies, selects, and synthesizes existing research on a specific topic to provide a comprehensive, transparent, and replicable overview of the current state of knowledge [102]. Moreover, SLR studies aim to extract the necessary data from relevant primary research papers, analyze the results, and synthesize the findings to gain deeper insights into the topic being investigated [103]. The overall process followed for SLR in this study is illustrated in *Figure 11*.

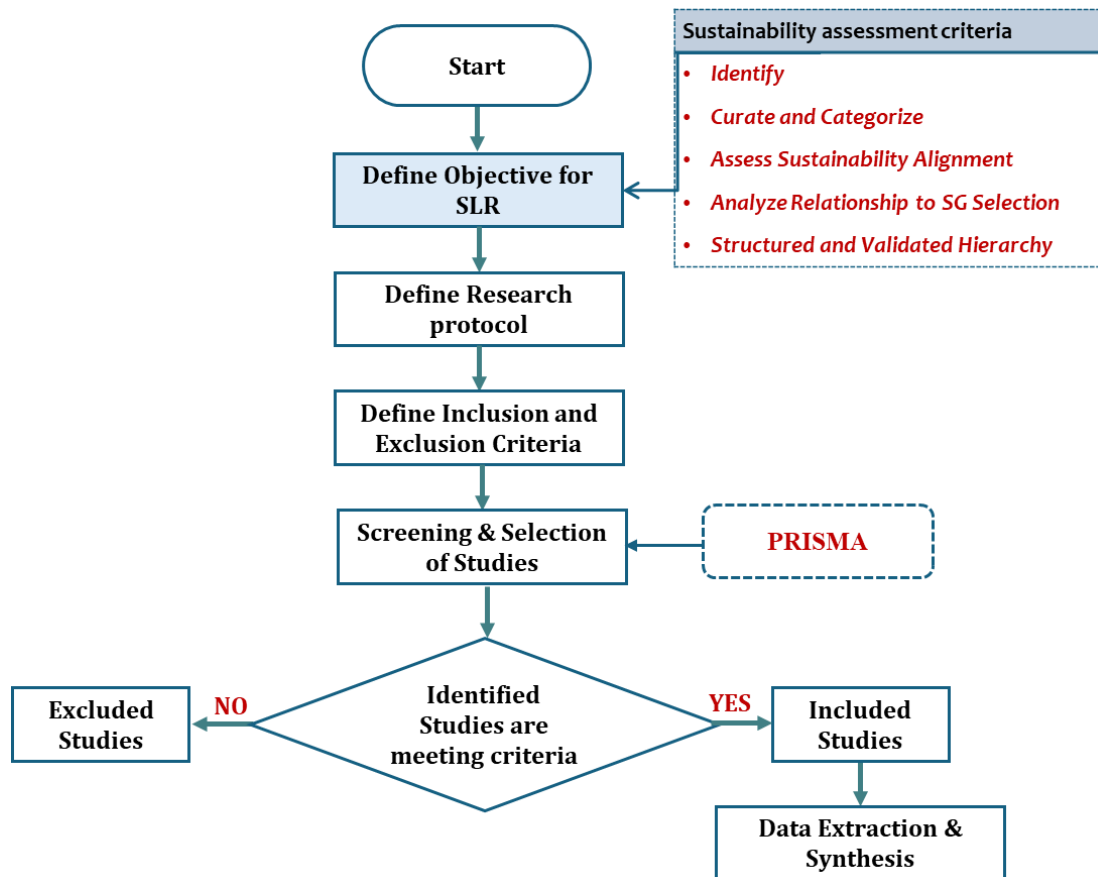


Figure 11: Systematic literature review (SLR) workflow

3.2.1 Objective

This study employs SLR, structured around the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [104] to achieve the specified objective of the study:

“To systematically identify, categorize, analyse, and synthesize sustainability assessment criteria for smart glazing technologies, ensuring a comprehensive evaluation of environmental, economic, technical, and social dimensions tailored to sustainable building applications.”

Following this research objective, the SLR addresses the following key aspects:

- To identify key sustainability assessment criteria used for evaluating smart glazing performance in non-domestic buildings in hot climates.
- To curate and categorize these criteria under the four sustainability dimensions: Environmental, Social, Economic, and Technical.
- To examine how these criteria align with the identified sustainability dimensions.
- To analyze the relationship between the sustainability criteria to smart glazing selection.
- To establish a structured and validated foundation for the subsequent sustainability assessment framework proposed by this research

3.2.2 Search Strategy

The search strategy was designed and implemented following the PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) guidelines [77]. The Scopus database was used in this study due to its extensive coverage as one of the largest curated abstract and citation databases, offering wide global and regional coverage of scientific

journals, conference proceedings, and books [105]. The details of the search process and the criteria used for this investigation are summarized in *Table 3*.

To determine the most appropriate keywords, preliminary searches were conducted to identify the various terminologies and classifications associated with smart glazing technologies. These searches revealed a variety of interchangeable terms commonly used within the field, such as "dynamic," "switchable," "advanced," "responsive," and "adaptive," all of which refer to aspects of smart glazing. Based on these insights, the following comprehensive set of search terms was crafted to encompass the broad scope of the research area:

TITLE-ABS-KEY ("smart glazing*" OR "dynamic glazing*" OR "switchable glazing*" OR "advanced glazing*" OR "responsive glazing*" OR "adaptive glazing*" OR "Electrochromic glazing*" OR "Suspended Particle Device glazing*" OR "Polymer Dispersed Liquid Crystal glazing*" OR "Liquid Crystal glazing*" OR "Gasochromic glazing*" OR "Thermochromic glazing*" OR "Photochromic glazing*" OR "Thermotropic glazing*" OR "PDLC glazing*" OR "SPD glazing*"

The Boolean "OR" operator was utilized to link terms within the same category, ensuring that the search captured all relevant literature about each type of smart glazing technology.

In addition to keyword searches, the search was further refined through the input parameters and criteria mentioned in *Table 3*.

The search included documents published from January 1985 to November 2024. The search was conducted in English to guarantee the clarity and accessibility of the studies reviewed. It was limited to peer-reviewed journal articles, conference papers, and reviews to ensure the reliability of the sources.

Table 3: Research protocol for SLR

Identified keywords/ Search query	TITLE-ABS-KEY ("smart glazing*" OR "dynamic glazing*" OR "switchable glazing*" OR "advanced glazing*" OR "responsive glazing*" OR "adaptive glazing*" OR "Electrochromic glazing*" OR "Suspended Particle Device glazing*" OR "Polymer Dispersed Liquid Crystal glazing*" OR "Liquid Crystal glazing*" OR "Gasochromic glazing*" OR "Thermochromic glazing*" OR "Photochromic glazing*" OR "Thermotropic glazing*" OR "PDLC glazing*" OR "SPD glazing*"
Database	Scopus
Search strategy	Boolean operators: AND, OR
Language	English
Search timeline	1985 – November 2024
Document type	Article, Conference paper, review
Source type	Limited to journals and Conference proceedings
Subject area	Engineering, Energy, Materials science, Physics and Astronomy, Environmental science, Multidisciplinary
Method	Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA-2020) framework

3.2.3 Inclusion and Exclusion Criteria

Clearly defined inclusion and exclusion criteria are essential for conducting a robust Systematic Literature Review (SLR), ensuring that only relevant, high-quality studies are selected for analysis. To maintain the review's rigor and focus, criteria were systematically established based on the research objectives, emphasizing smart glazing (SG) technologies specifically within the context of non-domestic buildings in hot climates.

The technology criterion was delineated to exclusively include dynamic smart glazing systems such as electrochromic (EC), suspended particle devices (SPD), polymer-dispersed liquid crystal (PDLC), thermochromic (TC), gasochromic (GC), and photochromic (PC) glazing, recognizing their unique potential in improving building sustainability. Conversely, conventional or static glazing solutions, including high-

performance glazing, low-emissivity (Low-E), or tinted glazing, were excluded due to their non-dynamic operational nature.

Given the specificity of the study's scope, building type was explicitly restricted to non-domestic structures, such as offices, educational facilities, and commercial buildings. Domestic buildings were intentionally excluded to maintain the relevance and applicability of findings to the targeted context, addressing the unique occupancy patterns, energy consumption profiles, and design standards of non-domestic environments.

Climatic context was another critical dimension for inclusion, focusing explicitly on hot climates such as hot-arid, hot-humid, tropical, subtropical, desert climates, and regions characterized by hot summers. This criterion aligns directly with the research aim of assessing sustainability impacts under conditions with substantial cooling demand, where smart glazing technologies can significantly enhance thermal and visual comfort and energy efficiency. Studies conducted in predominantly cold climates were deliberately excluded, as they present different sustainability considerations and glazing requirements.

Regarding publication language, only English-language studies were included to ensure consistency in interpreting and synthesizing the research content. This criterion was chosen to avoid potential linguistic biases or inaccuracies arising from translation. Moreover, to assure academic rigor and reliability, only peer-reviewed journal articles, systematic reviews, credible conference papers, and academic dissertations were considered. Non-peer-reviewed sources, such as industry reports, blogs, or general magazine articles, were excluded to uphold the scholarly credibility of the literature analyzed.

These comprehensive criteria, summarized in **Table 4**, collectively facilitated the selection of relevant, high-quality research that specifically aligns with the study's objective, thereby ensuring robustness and reliability in the subsequent synthesis and analysis stages.

Table 4: Inclusion and exclusion criteria for systematic literature review

Criteria	Inclusion	Exclusion
Technology Focus	Smart glazing technologies (e.g., EC, SPD, PDL, TC, GC, PC)	Conventional or non-dynamic glazing (e.g., high-performance, Low-E, tinted)
Building Type	Non-domestic (e.g., offices, commercial, educational)	Domestic buildings
Climate	Hot climates (hot-arid, hot-humid, tropical, subtropical, desert, Hot summers)	Cold-dominant climates
Language	English	Non-English
Document type	Peer-reviewed journal articles, reviews, conference papers, and dissertations	Non-peer-reviewed sources (e.g., blogs, industry reports, non-academic articles)

3.2.4 Screening and Selection

The systematic review process was conducted according to the PRISMA guidelines to ensure the comprehensive identification and selection of relevant studies on smart glazing technologies in non-domestic buildings situated in hot climates. This process was systematically documented and is illustrated in the PRISMA flowchart presented in **Figure 12**.

The initial search in the Scopus database yielded 548 records. This search, utilizing specific keywords targeting the abstracts, titles, and keywords of publications, was designed to comprehensively capture all potentially relevant articles.

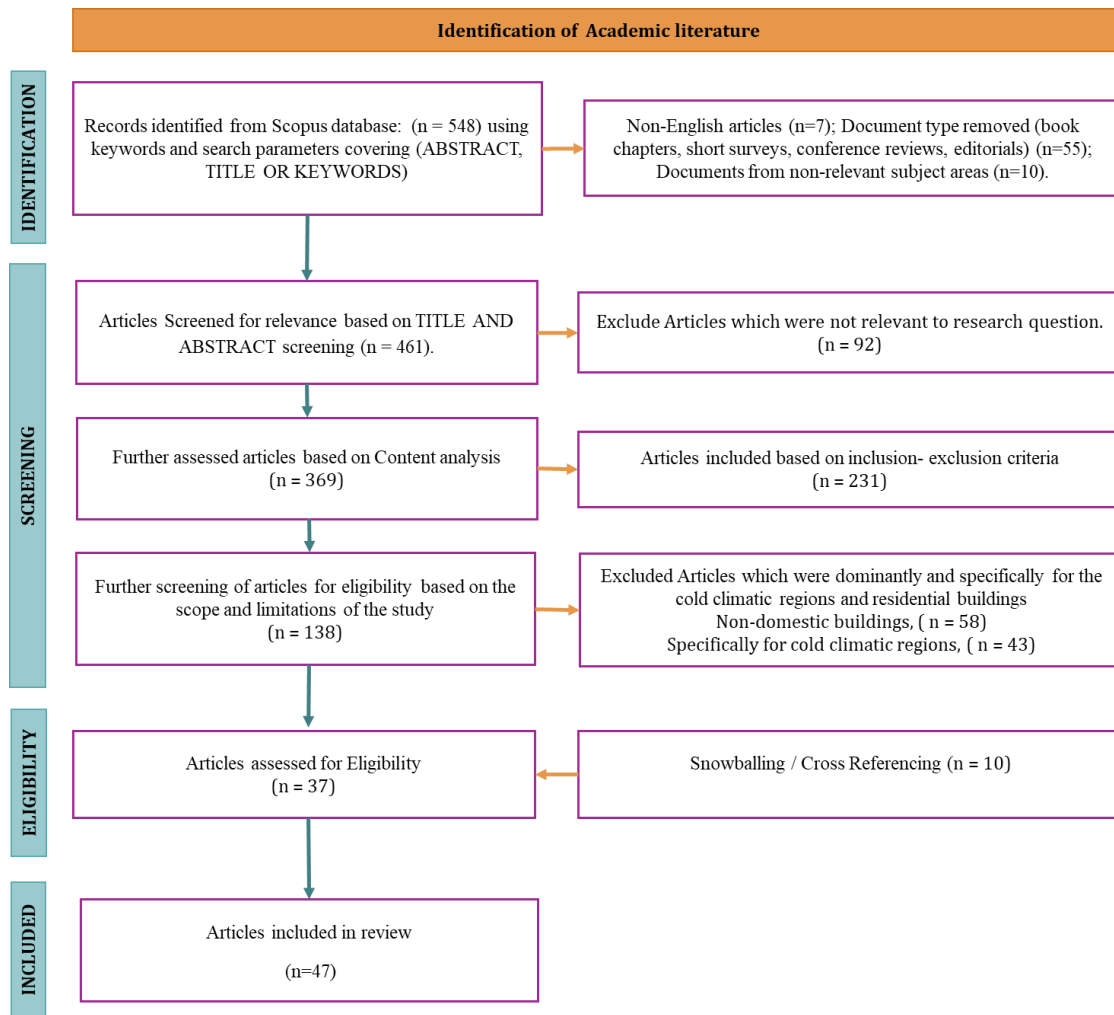


Figure 12: PRISMA flowchart

The study implemented a rigorous two-step screening process. The first screening stage focused on the titles and abstracts to determine relevance to the research questions concerning smart glazing technologies and their performance in buildings. This reduced the number of articles to 369. The second level of screening examined these articles for strict eligibility based on inclusion criteria (Table 4) that emphasized studies on smart glazing technologies specific to non-domestic buildings in hot climates, and excluding those without performance criteria discussions, such as energy, thermal, or visual performance. This phase significantly reduced the number to 138 articles.

Subsequently, a full-text review was conducted on these 138 articles to evaluate methodological rigor and relevance to the study's objectives, resulting in 37 articles being deemed eligible. Additionally, a snowballing technique was employed on the references of these 37 articles, uncovering an additional 10 studies that met the inclusion criteria but were not initially identified, bringing the total to 47 articles included in the systematic review.

3.2.5 Data Extraction

During the data extraction phase of the study, comprehensive data were systematically gathered from 47 scholarly articles that satisfied the inclusion criteria. This extraction process was organized into two primary types of information to ensure accuracy and thoroughness in capturing the essential aspects of each study, as illustrated in *Figure 13*.

Initially, **bibliographic details** of each study were extracted, which included the title, publication year, and the journal where each study was published. This information is foundational to assess the credibility, relevance and timeliness of the research findings, which are crucial for the integrity of the systematic review.

In the second phase of data extraction, detailed study characteristics were documented. This involved identifying the specific types of smart glazing technologies examined in each article, along with the various performance categories assessed, such as energy efficiency and thermal performance. For each category, specific performance indicators were noted, including metrics like energy consumption rates for heating, cooling, or lighting. The categories and indicators extracted are the core components of this study, serving as the foundational basis for subsequent analyses. Additional details regarding the type of

building, location of the study, and the climatic classification of these locations were also recorded.

Further, **Figure 13** visually illustrates the standardized data extraction template, highlighting the systematic cataloging of information.

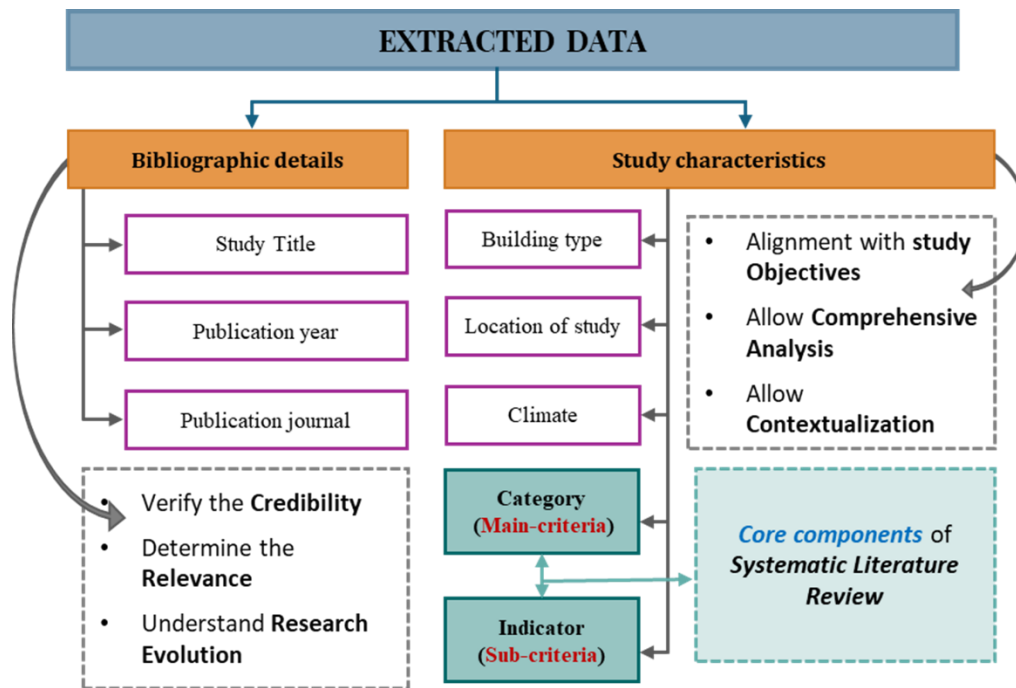


Figure 13: Extracted data format

3.2.6 Data Synthesis

After thorough data extraction from 47 scholarly articles, the synthesis phase was initiated to analyze, refine, and categorize the extracted data into structured and insightful conclusions (**Figure 14**). This phase is pivotal as it transforms the raw data into organized information that forms the basis for the entire study. The primary focus was on the identified assessment categories (main criteria) and indicators (sub-criteria), which are the core elements of this research.

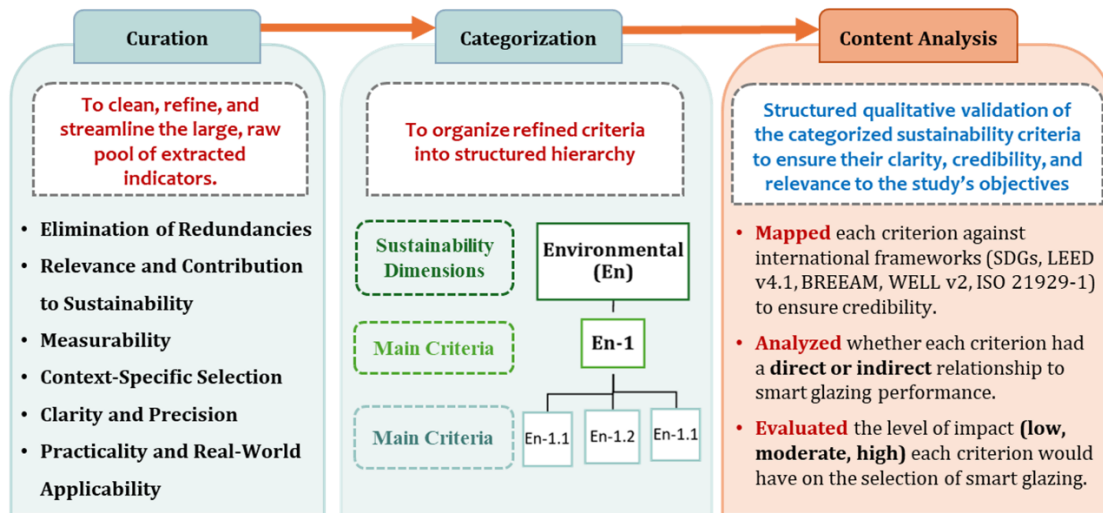


Figure 14: Data synthesis

3.2.6.1 Curation

The synthesis process began with the curation of data to ensure clarity and relevance. This involved a detailed review and refinement of the initially broad range of data collected. Developing a robust sustainability selection framework requires a comprehensive yet concise set of criteria. While a broad set of criteria enhances the validity and comprehensiveness of the selection framework, an overly extensive list can introduce unnecessary complexity and reduce transparency [106]. Therefore, a rigorous curation and categorization process was implemented to streamline the initial pool of sustainability criteria extracted from the literature. The goal was to refine the list to ensure clarity, conciseness, and relevance for the **Sustainability Assessment Framework (SG-SAF)** tailored to smart glazing technologies.

The initial review of literature uncovered a substantial array of potential indicators—approximately 518 items (**Appendix 1**). There were significant duplications that were removed primarily that resulted in 108 (**Appendix 2**). Still, many of these indicators exhibited significant overlap or redundancy, which necessitated a thorough curation

process. Even after eliminating the redundancies, the indicators, while comprehensive, were deemed excessive for the scope of this thesis. A systematic refinement process was applied to produce a concise and relevant list of criteria that aligned with the study's objectives. The further refinement process was guided by the following principles (*Table 5*):

- **Elimination of Redundancies**

Criteria with overlapping or redundant meanings were consolidated into single, comprehensive criteria. For instance, overlapping criteria such as "annual energy consumption," "monthly energy consumption," and "peak day energy consumption" were merged into a single indicator, total energy consumption (kWh/m²/year). This step ensured that each criterion was uniquely represented, reducing unnecessary complexity.

- **Relevance and Contribution to Sustainability**

Each criterion was evaluated for its substantial contribution to a comprehensive sustainability assessment. Indicators that did not significantly enhance the evaluation process were excluded, ensuring that the final list focused on critical aspects of sustainability. For example, CO₂ mitigation was prioritized for its critical role in assessing the environmental benefits of reducing cooling energy demands, while less impactful indicators, such as Urban Heat Island (UHI) Reduction, were excluded for being indirectly related to individual glazing systems.

Measurability

All selected criteria were required to be measurable, either quantitatively or qualitatively. This ensured that the framework could support accurate assessments and meaningful comparisons across smart glazing alternatives

- **Context-Specific Selection**

Criteria were selected to address the specific challenges and priorities associated with the study's scope, e.g., non-domestic buildings in hot climatic regions. For instance, indicators like cooling energy consumption and CO₂ mitigation were prioritized due to their importance in such environments.

- **Clarity and Precision**

Further, each criterion was analyzed for clarity and precision to ensure they are comprehensible and applicable in practical assessments. Ambiguous or poorly defined criteria were either clarified for better understanding or removed if they did not meet the clarity standards.

- **Practicality and Real-World Applicability**

Finally, the practicality of each criterion was assessed to confirm its applicability in real-world assessments of smart glazing technologies. This evaluation helped in discarding overly theoretical or impractical criteria, refining the list to those most applicable and beneficial for stakeholders involved in the selection and implementation of smart glazing solutions.

Through these curation steps, the initial list of indicators (sub-criteria) was effectively condensed and refined as summarized in, setting a solid foundation for the subsequent categorization phase, which organizes these criteria into a structured hierarchy.

Table 5: Comprehensive curation summary

Curation Step	No. of Sub-criteria Removed	Sample Examples
• Initial Identification from Literature	–	518 sub-criteria initially identified
• Visible Duplication Removal (Prime Step)	410	Multiple occurrences of SHGC, U-value, VLT
• Further curation steps applied (on remaining 118 indicators):		
(a) Elimination of Redundancies	26	• Monthly and annual energy consumption (<i>merged into total energy consumption</i>)
(b) Relevance and Contribution to Sustainability	12	• Urban Heat Island (UHI) reduction (<i>indirect relevance to glazing performance</i>)
(c) Measurability	8	• Circadian stimulus potential (<i>unclear measurement method</i>)
(d) Context-Specific Selection	6	• Heating energy consumption (<i>irrelevant for hot climate scenarios</i>)
(e) Clarity and Precision	5	• Solar modulation (<i>ambiguous and imprecise definition</i>)
(f) Practicality and Real-World Applicability	4	• Infrared hemispherical emissivity (<i>complex and impractical in standard settings</i>)
Final Curated Set of Indicators	47 sub-criteria under 9 main criteria	

3.2.6.2 Categorization

The categorization process systematically organized the refined list of sub-criteria into a structured hierarchy for the sustainability assessment of smart glazing technologies. This hierarchy was divided into four primary sustainability dimensions: **Environmental (En)**, **Social (S)**, **Economic (Ec)**, and **Technical (T)**. To ensure clarity and alignment with the study's objectives, the hierarchy was further divided into two levels: Level 1 for main criteria and Level 2 for sub-criteria, as illustrated in *Figure 15*.

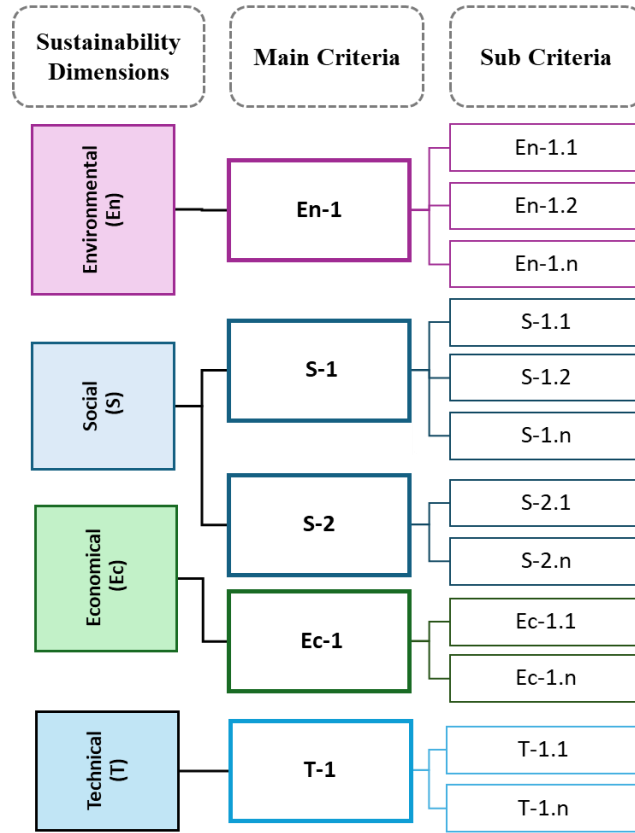


Figure 15: Schematic showing classification of criteria under four sustainability dimensions

3.2.6.3 Content Analysis

A structured qualitative content analysis was conducted to validate and finalize the classification of sustainability criteria into the four core dimensions: Environmental, Social, Economic, and Technical. This process aimed to ensure that each criterion was conceptually clear, practically relevant, and contextually appropriate for evaluating smart glazing technologies in non-domestic buildings in hot climates. The following specific factors were analyzed:

- Criteria were evaluated for their applicability as sustainability indicators and mapped against internationally accepted frameworks such as the SDGs, LEED v4.1, BREEAM, WELL v2, and ISO 21929-1 to ensure credibility and traceability in classification.

- The relationship (direct or indirect) and the level of impact (low, moderate, high) of each sustainability criterion on smart glazing selection were evaluated. **This analysis was conducted with the assistance of AI tools to ensure a structured and consistent evaluation of each criterion. The most frequently occurring outputs were considered for the final assessment.**

To further validate the findings and prioritize the identified sustainability criteria, the next phase involved conducting a structured questionnaire. This step served two main purposes: (1) to obtain expert validation of the classified criteria through professional judgment, and (2) to determine the relative importance of each main criterion by asking experts to rank them. These rankings will serve as the basis for assigning weightings in the upcoming decision-making model, ensuring that the framework reflects expert consensus and real-world relevance.

3.3 Questionnaire (S5): Validation and Prioritization of Criteria

Figure 16 presents a visual summary of the structured methodology adopted for the expert questionnaire survey. It outlines the clear sequence from defining the survey objectives through questionnaire design, implementation procedures including expert sampling techniques, and detailed approaches for the analysis of survey results.

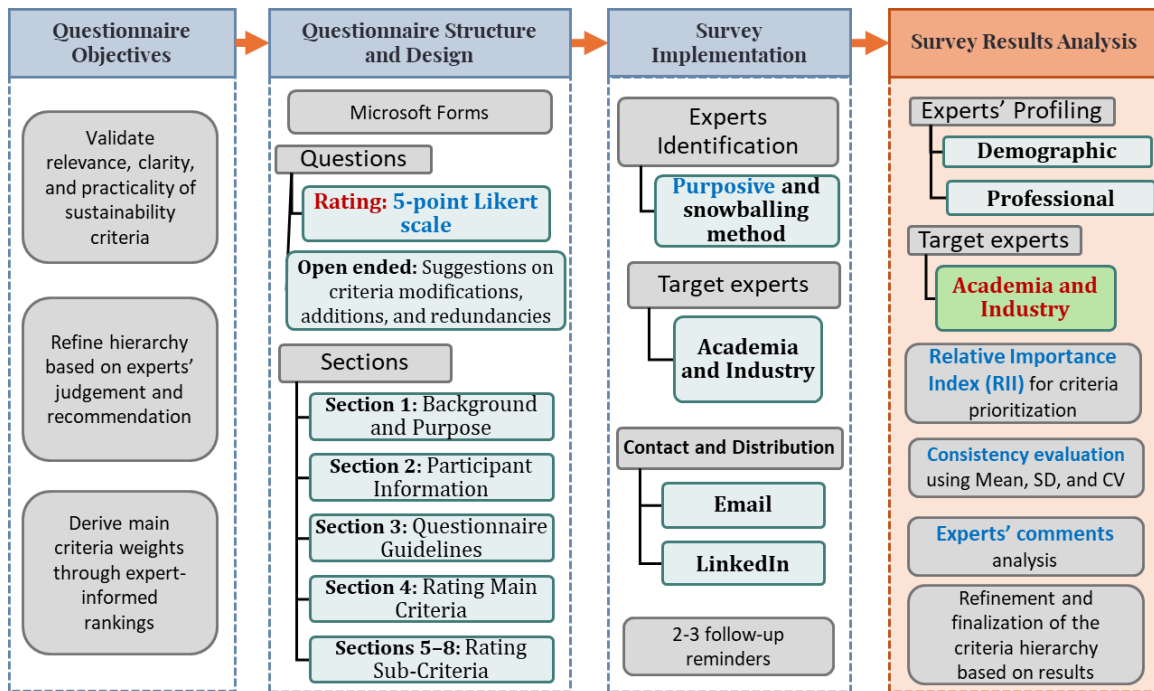


Figure 16: Methodological overview of questionnaire survey

3.3.1 Purpose of the Questionnaire

To build upon the categorization achieved through the content analysis and ensure its applicability in real-world decision-making, it was essential to seek external expert validation. While the literature-based framework established a robust theoretical foundation, the practical implementation of the SG-SAF required confirmation of the relevance, clarity, and significance of each criterion. Additionally, to streamline the framework for usability, it was necessary to determine the relative importance of each main criterion through stakeholder-informed prioritization. Therefore, a structured expert questionnaire was designed and administered. This Questionnaire will serve two primary functions: **(1)** to validate the curated criteria and sub-criteria by capturing insights from both academic and industry professionals with experience in sustainable building technologies and smart glazing systems, and **(2)** to derive weights for each main criterion using expert-informed rankings. These weightages would later serve as the basis for

informed decision-making in the multi-criteria assessment framework, enhancing its reliability, credibility, and practical utility in hot-climate, non-domestic building contexts. Specifically, respondents were asked to:

- Confirm the relevance, practicality, and clarity of the curated criteria and sub-criteria.
- Prioritize the criteria based on perceived importance using expert-informed rankings.
- Identify and suggest the elimination or consolidation of less significant or overlapping criteria to streamline the framework.
- Provide additional suggestions for refining existing items or introducing missing elements in the current hierarchy.

By addressing these objectives, the questionnaire served as a critical step in ensuring the robustness and practical utility of the SG-SAF, specifically for non-domestic buildings in hot climatic regions.

3.3.2 Questionnaire Structure and Design

The questionnaire was designed to collect expert feedback on the perceived importance, relevance, and practicality of the identified criteria and sub-criteria for selecting sustainable smart glazing technologies. The primary focus of the survey questions was to:

- To rate the perceived importance of the identified criteria and sub-criteria under Environmental, Social, Economic, and Technical dimensions.
- To ensure that the selected criteria effectively capture critical sustainability aspects.
- To assess the practicality of these criteria for real-world applications, particularly in non-domestic buildings in hot climatic regions.
- To gather qualitative feedback on possible refinements, additions, or overlaps in the criteria.

For this purpose, a **five-point Likert scale** was employed, where participants rated each criterion and sub-criterion. The Likert scale (1–5) used for the study was labelled as **1 = Not Important, 2 = Less Important, 3 = Moderate, 4 = Important, 5 = Very Important**.

The questionnaire was developed using **Microsoft Forms** for ease of accessibility and completion. It was divided into the following sections:

Section 1: Background and Purpose

This section introduced the study's objectives, the purpose of the questionnaire, and the importance of expert feedback.

Section 2: Participant Information

In this section, participants were asked to provide demographic and professional details, such as:

- Name and contact information
- Title/position and organization
- Areas of expertise
- Years of experience in relevant fields

Section 3: Questionnaire Guidelines

Detailed instructions on completing the questionnaire were outlined in this section, including:

- A description of the 5-point Likert scale (1 = Not Important to 5 = Very Important).
- Steps to rate main criteria and sub-criteria under the four sustainability dimensions.
- Guidance on providing additional feedback, such as suggesting modifications, proposing new sub-criteria, or identifying redundancies.

Section 4: Rating Main Criteria

In this section participants were asked to rate the **main criteria** under each sustainability dimension (Environmental, Social, Economic, and Technical) based on their perceived importance in selecting sustainable smart glazing systems.

Sections 5–8: Rating Sub-Criteria

These sections were dedicated to rating the **sub-criteria** under each main criterion based on their perceived importance in selecting sustainable smart glazing systems, within the four sustainability dimensions:

- **Section 5:** Environmental dimension sub-criteria.
- **Section 6:** Social dimension sub-criteria.
- **Section 7:** Economic dimension sub-criteria.
- **Section 8:** Technical dimension sub-criteria.

Sections 4 through 8 formed the core of the questionnaire, focusing on the rating of criteria and sub-criteria under the Environmental, Social, Economic, and Technical dimensions using a five-point Likert scale (1 = Not Important to 5 = Very Important). These sections directly addressed the perceived importance and applicability of the identified hierarchy in selecting sustainable smart glazing technologies. In addition to quantitative ratings, each section included open-ended questions to collect qualitative insights from participants. These questions encouraged participants to:

- Suggest modifications or elaborations on the existing criteria or sub-criteria.
- Propose new criteria or sub-criteria deemed important but not currently included.
- Identify overlaps or redundancies between criteria or sub-criteria.
- Provide general feedback or additional comments.

The questionnaire can be seen in **Appendix 3**.

3.3.3 Survey Implementation/ Survey Approach and Expert Sampling

3.3.3.1 Criteria for Expert Selection

The survey implementation process began with the identification of relevant research participants. To ensure the collection of robust and credible insights, a **purposive sampling**

strategy was employed. This method involves the intentional selection of individuals based on specific characteristics, knowledge, or expertise relevant to the research objectives [107]. It is widely used in qualitative research for identifying and selecting information-rich cases that can provide meaningful input, especially when resources are limited [108]. Selection criteria also included the participants' availability, willingness to contribute, and ability to express expert opinions clearly and reflectively.

Initially, purposive sampling was used to identify experts and researchers with substantial academic or industry experience related to smart glazing systems. This was followed by snowball sampling, whereby initial respondents were invited to recommend additional experts who possessed significant knowledge in relevant domains.

Given the niche nature of the topic, identifying sufficient participants solely within the domain of smart glazing proved to be a significant challenge. To address this, the scope of expertise was broadened to include professionals and academics with foundational knowledge or relevant experience in smart glazing technology, alongside expertise in the following key areas:

- Sustainable building design and construction
- Advanced glazing systems and technologies
- Building envelopes and facades
- Energy efficiency and building performance
- Energy-efficient buildings
- Building lifecycle assessment and environmental impact
- Smart or sustainable building materials
- Related fields of expertise

Based on these criteria, the target participants included architects, facade engineers/consultants, building physicists, building engineers, building materials scientists/engineers, and sustainability consultants, as well as academically affiliated researchers.

3.3.3.2 Expert Identification and Recruitment Channels

Academic professionals and researchers were identified primarily through a review of literature and research papers focused on smart glazing systems and related fields. Authors of these studies were contacted directly via the email addresses provided in the publications. In total, approximately **40 researchers/experts** were contacted via email, and three follow-up reminders were sent to encourage participation. Industrial and academic professionals and researchers were also identified and contacted through LinkedIn, focusing on individuals whose profiles indicated expertise in the relevant areas. Around **100 experts** were approached using LinkedIn messaging, with two follow-ups and, in some cases, three to ensure maximum response rates. Hence, the questionnaire was disseminated online using two primary methods:

1. **Email:** Academic experts and researchers identified through the literature review were contacted directly via email.
2. **LinkedIn Messages:** Industry professionals and academics with relevant expertise were engaged through personalized LinkedIn messages.

After the initial distribution, two follow-up reminders were sent to all identified participants to maximize response rates and ensure robust feedback.

3.3.4 Analysis of Survey Results and Data Interpretation

Following the completion of the questionnaire, a systematic analysis was conducted to evaluate the responses. Microsoft Excel was employed to process and analyse the collected data, ensuring precision and consistency in interpretation. The methodology involved multiple stages, including demographic and professional background analysis, quantitative analysis, and ranking of criteria based on expert evaluations. The subsequent sections provide a detailed methodology of these key analytical steps.

3.3.4.1 Respondent Profile and Professional Background

A comprehensive analysis of respondent demographics and professional background was conducted to ensure the credibility and diversity of the expert pool. Participants were categorized based on the following parameters:

- Professional role (e.g., researcher, professor, architect)
- Years of experience
- Areas of expertise
- Organization type (academic, industrial, consultancy)

3.3.4.2 Geographic location

By systematically organizing this information, the study established a structured approach to understanding the composition of participants, ensuring a balanced representation of academic researchers, industry professionals, and sustainability experts across multiple sectors and regions. Additionally, the analysis assessed the distribution of experts across academia and industry to verify the breadth of insights incorporated into the study. This categorization facilitated an evaluation of how professional experience and background influence perspectives on sustainable smart glazing technologies.

By methodically profiling respondents, this study ensured that subsequent evaluations and prioritization of sustainability criteria was derived from a well-qualified and diverse group of experts. This structured approach strengthened the validity and applicability of the findings and provided a robust foundation for subsequent data interpretation.

3.3.4.3 Relative Importance Index (RII)

The Relative Importance Index (RII) is a widely recognized statistical method used to evaluate and rank the relative significance of various factors or criteria based on participant responses. It provides a structured approach to prioritizing criteria by assigning them a numerical value that ranges between 0 and 1, where higher values indicate greater importance. This method is frequently employed in studies to assess perceptions and establish the relative significance of criteria [109, 110].

The objective of this analysis is to prioritize sustainability criteria and sub-criteria based on expert evaluations, ensuring that only the most relevant factors are retained in the decision-making framework. The Relative Importance Index (RII) was calculated using the following equation:

$$\text{RII} = \frac{\sum W}{A \times N} \quad (1)$$

Where:

- W : Weight assigned to each criterion by respondents (on a Likert scale of 1–5 in this study).
- A : Maximum possible weight (in this case, 5).
- N : Total number of respondents.

The resulting RII values were interpreted based on the scale proposed by Chen et al. (2010) [111, 112] as shown in Table 6. This ranking method enabled the identification of the most

significant criteria and sub-criteria, which were retained and prioritized in the final framework.

Table 6: Importance level based on RII values [111, 112]

Rank	RII value
Very high	$0.8 < \text{RII} < 1.00$
High	$0.6 < \text{RII} < 0.8$
Moderate	$0.4 < \text{RII} < 0.6$
Low	$0.2 < \text{RII} < 0.4$
Very low	$0.0 < \text{RII} < 0.2$

3.3.4.4 Mean, Standard Deviation (SD), and Coefficient of Variation (CV)

In addition to RII, the Coefficient of Variation (CV) was used to assess the consistency of expert responses. It is defined as the ratio of the standard deviation to the mean, expressed as a percentage. CV was calculated using the following equation [113]:

$$\text{CV} = \frac{\text{Standard Deviation}}{\text{Mean}} \times 100 \quad (2)$$

Interpretation of CV values was based on the following classification [114]:

- $\text{CV} < 20$: Low variability
- $20 < \text{CV} < 30$: Moderate variability
- $\text{CV} > 30$: High variability
- $\text{CV} > 50$: Very high variability

By employing this methodology, each criterion and sub-criterion was systematically ranked according to its perceived importance. The moderate to least important criteria and sub-criteria were eliminated. The rankings informed the practicality and further refinement of the earlier identified and categorized hierarchy, ensuring that the framework emphasized the most critical sustainability criteria and sub-criteria while excluding or de-emphasizing less significant ones.

3.4 Data Collection for Decision Matrix (S7)

To develop a comprehensive decision matrix for evaluating and selecting sustainable smart glazing systems, performance data for each sustainability sub-criterion were systematically collected across all identified alternatives. The dataset included both quantitative and qualitative values categorized under the four core sustainability dimensions: Environmental, Social, Economic, and Technical.

An iterative methodology was adopted to determine the most appropriate strategy for collecting performance data. Initially, expert-based methods were considered; however, this approach proved impractical due to several constraints. These included many sub-criteria and alternatives, time limitations for data collection, and low commitment from experts to complete lengthy comparative surveys.

Subsequently, a literature-based data collection approach was explored. While valuable, it was found insufficient for several sub-criteria due to the variability of contexts across existing studies (e.g., differing climatic zones, building typologies, and inconsistent performance reporting), making it difficult to synthesize reliable and comparable values for the decision matrix. As a result, a **hybrid approach** was adopted as the final strategy. This involved:

- Simulating performance data for Environmental and Social criteria using a **calibrated DesignBuilder model** of a real non-domestic office building in a hot-arid climate (Riyadh, Saudi Arabia).
- Collecting Technical and Economic data primarily from peer-reviewed literature, manufacturer specifications, supplier quotes, and technical datasheets.

This final approach ensured that the collected data were context-specific, comparable, and standardized across all glazing alternatives. The methodological flowchart illustrating this performance data collection process is presented in Figure 17.

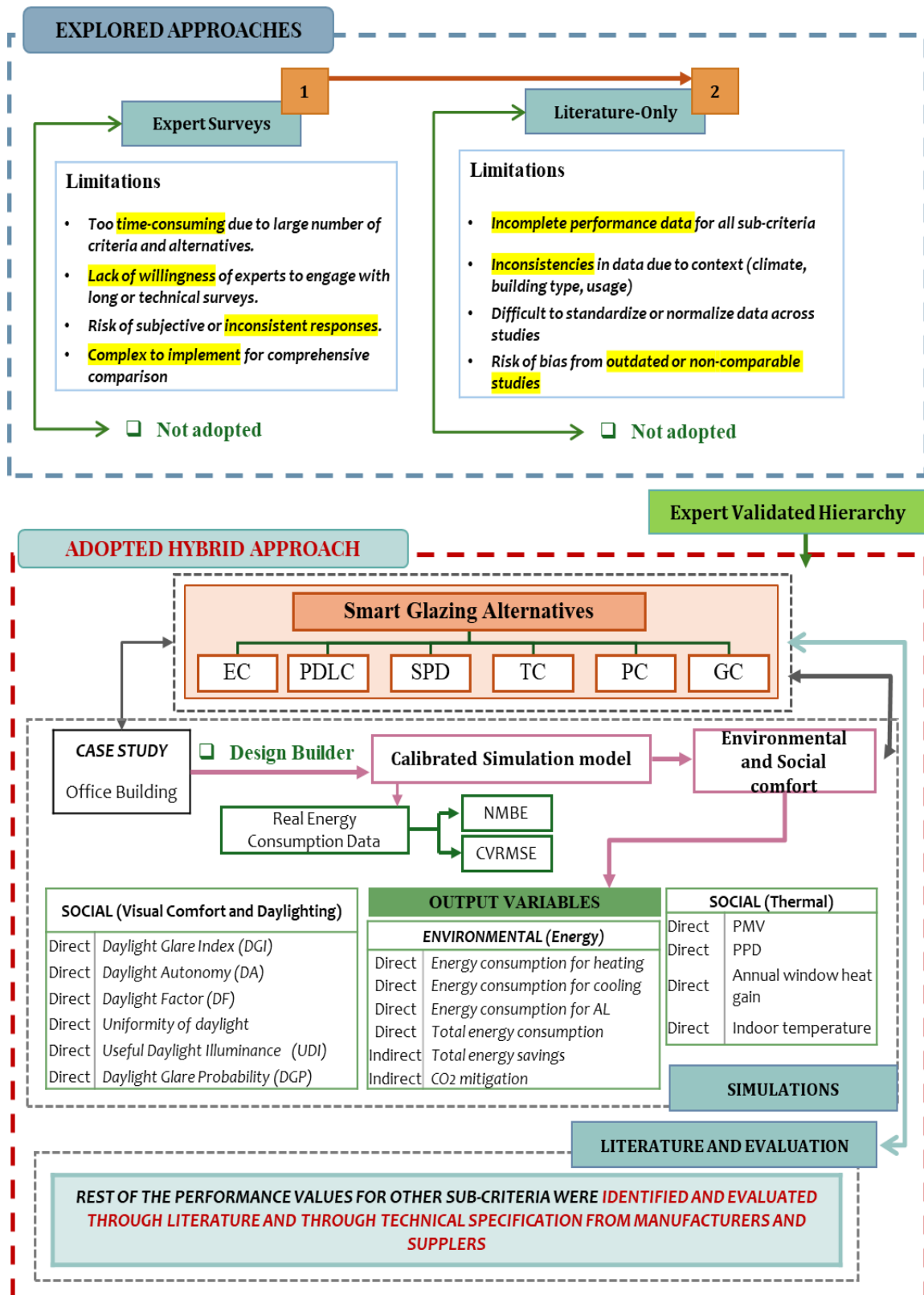


Figure 17: Methodological overview for performance data collection

3.4.1 Identification and Selection of Smart Glazing Alternatives

The identification of smart glazing alternatives was based on an extensive literature review, which categorized various glazing technologies into Passive and Active systems, as discussed earlier. Given the wide range of glazing options available, it was necessary to select a representative glazing system for each alternative to ensure consistency and comparability in the assessment process. However, this selection process was influenced by several constraints and considerations, particularly the focus on single-glazed systems. To maintain rigor and systematic selection, specific principles were followed to ensure that the chosen glazing systems accurately represented their respective alternatives while ensuring consistency in performance evaluation.

The selection of representative **single-glazed** smart glazing alternatives was based on the following key constraints and considerations:

- The primary objective of this assessment was to evaluate the performance of smart glazing systems. While single-glazing systems are generally less favourable for non-domestic buildings, they were chosen to ensure comparability across alternatives due to the unavailability of consistent data for identical double- or triple-glazing systems.

(Ensuring Comparability)

- Although double- or triple-glazed systems could be simulated using tools such as WINDOW 7.8 or DesignBuilder, their selection was restricted due to the lack of comprehensive input data, particularly for products that are not commercially available.

(Limitations in Input Data)

- A thickness range of 6–9 mm was maintained across all selected alternatives to ensure uniformity in the analysis. **(Standardized thickness range)**

- Among the multiple glazing options available with similar thickness for each alternative, simulations were conducted to evaluate their performance. The glazing systems that exhibited superior energy efficiency, solar heat reduction, and daylighting performance in hot climatic regions were prioritized for selection. **(Performance-Based Selection)**
- Preference was given to commercially available smart glazing due to the availability of validated performance data. Systems with reliable and comprehensive data, sourced from technical datasheets, manufacturer specifications, or simulation tools such as WINDOW 7.8, were prioritized over those studied solely in academic research. **(Commercial Availability)**
- For smart glazing alternatives with limited commercial availability, peer-reviewed literature was used to ensure reliability and alignment with the study's objectives. **(literature reliability)**
- Since single-glazed glazing systems were selected for each alternative, a 6 mm single-glazed base case glazing was used as a reference to ensure a consistent and comparable assessment framework across all alternatives

These principles ensured a systematic and transparent approach to selecting representative glazing systems.

Table 7 summarizes the selected smart glazing alternatives along with their specifications, showcasing the systems that best exemplify the characteristics of each smart glazing category. These selections serve as the foundation for acquiring the performance values necessary for the sustainability assessment framework.

Table 7: Selected smart glazing alternatives

Sr. no	Smart Glazing Alternative	ID	Composition	Manufacturer/Supplier	Th. mm	SHGC	U-value W/m ² K	VLT	Tint colour	Reff.
						Tinted /Opaque e		Tinted /Opaque e	Fully tinted state	
1	Base case	A	Monolithic	Existing	---	0.8	5.5	0.8		Existing Energy Plus Database
2	Electrochromic (EC)	A7	Laminated	SAGE	07	0.18	3.523	0.014	Black	
3	Polymer Dispersed Liquid Crystal (PDLC)	A1	Laminated	Literature	08	0.317	5.646	0.38	Milky Opaque White (off state)	[115]
4	Suspended Particle Device (SPD)	A8	Laminated	Literature	08	0.05	5.9	0.05	Dark blue	[38, 116]
5	Thermochromic (TC)	A6	Monolithic	LBNL	07	0.499	5.7	0.086	25 -75 C / Olive green	Energy Plus Database
6	Thermotropic (TC)	A9	Laminated	Fraunhofer IAP	09	0.59	5.74	0.46	20-40 C/ Greenish white	[46, 117]
7	Photochromic (PC)	A10	Laminated	Literature	08	0.44	5.81	0.11	Deep blue	[49]
8	Gassochromic (GC)	A4	Monolithic	Literature	06	0.52	2.6	0.54	Deep blue	[72]

SHGC: Solar Heat Gain Coefficient, **U-value:** Thermal Transmittance, **VLT:** Visible Light Transmittance, **Th.:** Thickness

3.4.2 Case Study Description

To acquire quantitative performance data for smart glazing alternatives under environmental and social sustainability criteria, a representative non-domestic office building was selected for detailed simulation. The chosen building, located in Al-Khobar, Saudi Arabia, aligns closely with the study's emphasis on highly glazed non-domestic buildings. Its prior use in research related to HVAC system performance and dynamic façade energy efficiency further supports its relevance and reliability as a case study [118].

The building features a square footprint ($30\text{ m} \times 30\text{ m} \times 41\text{m}$) with an east-facing main entrance, as shown in Figure 18. It comprises nine floors, totalling $8,400\text{ m}^2$ of built-up area, with each typical floor covering 862 m^2 and the mezzanine floor 642 m^2 . The first to fourth and sixth to seventh floors have similar layouts, whereas the ground, mezzanine, fifth, and eighth floors each have unique configurations. The building's detailed floor layouts are shown in Figure 19, while Table 9 provides a breakdown of the zoning distribution, occupancy status, and glazed façade orientation for each floor and zone. The detailed physical characteristics of the simulation model are provided in *Table 8*.

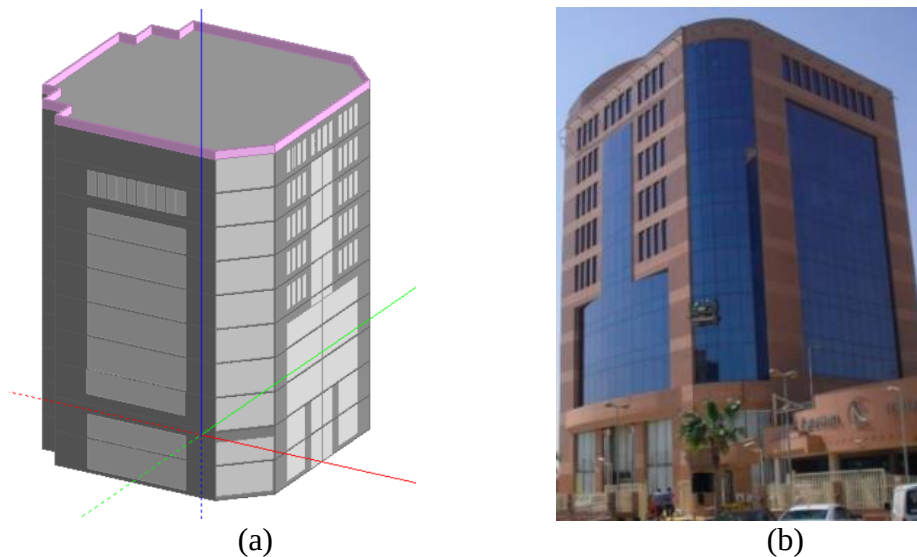


Figure 18: Case study: (a) Simulated model in Design builder, (b) Real building image

Table 8: Physical characteristics of the case study

Characteristics	Description
Building location	Khobar, Saudi Arabia
Simulation location	Riyadh, Saudi Arabia Latitude N 24.71°, Longitude E 46.73° Hot desert climate
Building type	Office (non-Domestic)
Geometry	Square
Floor area	Total: 8400 m ² Each Standard Floor: 862 m ² Mezzanine Floor: 642 m ²
Total Floors	09 floors
Total Height	40.73 m
Gross Wall Area	4578.84 m ²
Window opening Area	1770.48 m ²
HVAC system	Packages single Zone
WWR	Overall: 38.66% North: 50.67 %, South: 54.66%, East: 47.09%, West: 5.93%
Type of Glazing	Double Glazed-Clear 6/6/6 mm, Reflective Double Glazed-Tinted 6/6/6 mm
External Walls	Granite cladding precision-cut to a thickness of 20 mm is followed by a layer of concrete hollow block measuring 150 mm. Subsequently, a 12.5 mm thick gypsum board is installed, serving as the substrate for the final layer of paint.
Roof	A 15 mm layer of cement plaster is succeeded by a reinforced concrete slab with a thickness of 200 mm, topped with asphalt tiles.
Floor	A layer of heavyweight concrete measuring 100 mm is followed by a 25 mm thickness of mortar cement, and the topmost layer consists of 25 mm terrazzo.
Building selection criteria	Representative of office buildings in hot climatic regions, High Glazing-to-Wall ratio, Representative climate context, Availability of energy data

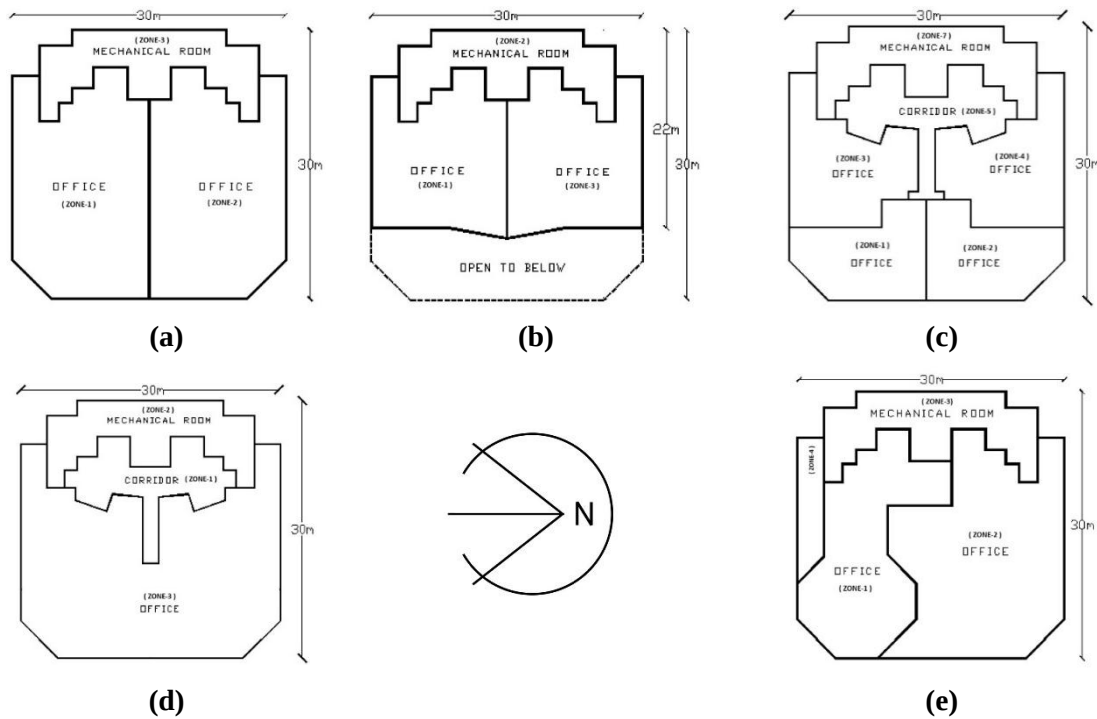


Figure 19: Floor plans of the building (a) Ground floor, (b) Mezzanine floor, (c) Typical first to seventh floors, (d) Fifth floor, (e) Eighth floor

Table 9: Floor-wise zoning, occupancy, and glazing orientation

Floor	Zones	Label	Occupancy consideration	Facade with glazing
Ground	Zone-1	Office	Occupied	S, SE, E
	Zone-2	Office	Occupied	N, NE, E
	Zone-3	Mechanical room (MR)	Un-occupied	SW, W, NW
Mezzanine	Zone-1	Office	Occupied	S, SE, E
	Zone-2	MR	Un-occupied	SW, W, NW
	Zone-3	Office	Occupied	N, NE, E
First	Zone-1	Office	Occupied	E, SE
Second	Zone-2	Office	Occupied	E, NE
Third	Zone-3	Office	Occupied	S
Forth	Zone-4	Office	Occupied	N
Sixth	Zone-5	Corridor	Occupied	No exterior glazing
Seventh	Zone-7	MR	Un-occupied	SW, W, NW
Fifth	Zone-1	Corridor	Occupied	No exterior glazing
	Zone-2	MR	Un-occupied	SW, W, NW
	Zone-3	Office	Occupied	S, SE, E, NE, N
Eight	Zone-1	Office	Un-occupied	S, E
	Zone-2	Office	Un-occupied	E, NE, N
	Zone-3	MR	Un-occupied	SW, W, NW
	Zone-4	Un specified	Un-occupied	S

The building was modelled and simulated using **DesignBuilder (Version 7.3.0.040)**, as depicted in (a) Figure 18, with its physical characteristics summarized in Table 8. The selection of this case study was based on several key considerations:

- **Alignment with the study's focus on non-domestic buildings**, ensuring relevance to the research objectives.
- **A highly glazed facade**, facilitating an effective assessment of different smart glazing alternatives, particularly in terms of energy efficiency, visual comfort, daylighting, and thermal comfort.
- **Representative of office structures in hot climatic regions**, allowing for generalizable insights applicable to similar architectural typologies.
- **Availability of comprehensive energy consumption data**, sourced from utility bills, which is essential for accurate simulation and validation.

Thus, this office building, with its high glazing-to-wall ratio, serves as an optimal candidate for evaluating smart glazing performance concerning energy efficiency, visual comfort, daylighting, thermal comfort, and energy-related cost assessment.

3.4.3 Calibration Methodology for the Simulation Model

The accuracy of a building simulation model depends on its validation against actual measured data. This validation process involves comparing actual measured data with simulation outputs to ensure the model's predictive accuracy. A well-calibrated model increases confidence in its ability to replicate actual building performance, making it a reliable tool for assessing the energy performance of buildings when adequately calibrated [119, 120].

To ensure model reliability, this study employs the combination of the Coefficient of Variation of the Root Mean Square Error (CVRMSE) and the normalized mean bias error (NMBE) as key calibration metrics. CVRMSE measures the relative variability of

prediction errors, indicating model precision by dividing the Root Mean Square Error (RMSE) by the mean value of observed data. A lower CVRMSE signifies a more precise model with reduced variation in prediction errors. Normalized mean bias error (NMBE) evaluates the bias or systematic error of the model by dividing the Mean Bias Error (MBE) by the mean value of observed data and expressing it as a percentage. Lower NMBE values indicate a model with less bias, where predicted and observed average values are closer. [119, 121].

The integration of CVRMSE and NMBE offers a comprehensive assessment of model performance. While CVRMSE evaluates prediction accuracy, NMBE identifies bias, providing insight into model strengths and limitations. Their adaptability allows for iterative refinements, making them effective tools for model evaluation and enhancement. Tracking variations in CVRMSE and NMBE values facilitates comparison between different model versions, parameter adjustments, and overall accuracy improvements. [119]

ASHRAE Guideline 14 establishes limits for NMBE and CVRMSE, as presented in **Table 10**, defining acceptable accuracy levels for model calibration

Table 10: Calibration criteria of ASHRAE guidelines 14 [122]

Data type	Index	ASHRAE Guidelines 14
Monthly (%)	NMBE	± 5
	CVRMSE	15
Hourly (%)	NMBE	± 10
	CVRMSE	30

The simulation model was developed and calibrated using **DesignBuilder Version 7.3.0.040**, utilizing **12 months of actual energy consumption data from utility bills**. The

calibration process involved testing the model with three different weather datasets for Dhahran, covering the periods 2009–2023, 2004–2018, and 2007–2021. These datasets were integrated into the simulations to assess their impact on energy predictions and select the dataset that best aligned with measured energy consumption. The calibration process is summarized in *Figure 20*.

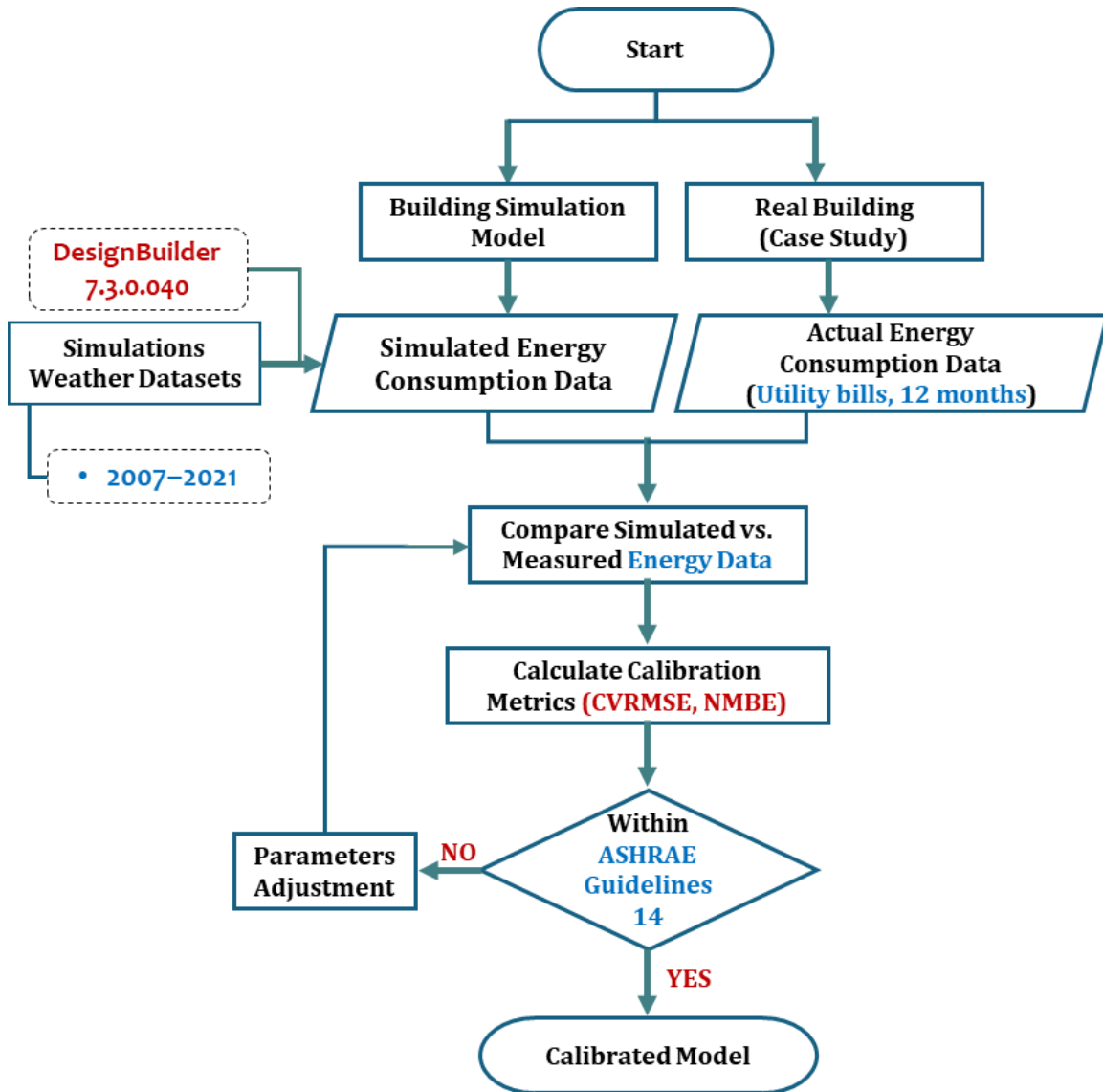


Figure 20: Calibration process of the model

The calibration process followed the validation equations outlined by ASHRAE Standard 140 and Guideline 14. The NMBE and CVRMSE values were calculated using the following equations:

$$NMBE = \frac{MBE}{\bar{r}} \times 100 = \frac{\sum_{k=1}^n (r - p)}{n - \bar{r}} \times 100 \quad (3)$$

$$CVRMSE = \frac{RMSE}{\bar{r}} \times 100 = \frac{\sqrt{\frac{\sum_{k=1}^n (r - p)^2}{n}}}{\bar{r}} \times 100 \quad (4)$$

Where,

- $\bar{r}$ is the mean of the measured values
- r is the measured value
- p is the simulated value
- n is the number of data point(s).

By implementing this calibration approach, the simulation results align closely with actual energy consumption, ensuring the model accurately represents real-world performance. This enhances the study's credibility and provides a robust foundation for evaluating smart glazing alternatives concerning energy efficiency, daylighting, and occupant comfort.

3.4.4 Simulation Setup for Smart Glazing Systems

The performance evaluation of the selected smart glazing alternatives was conducted using **DesignBuilder v7.3.0.40**, a widely recognized simulation software for building energy performance and daylighting analysis. The primary objective was to derive performance values for environmental and social sub-criteria, using the calibrated case study model of a non-domestic office building. Riyadh's hot-arid climatic conditions were selected to assess glazing performance under extreme thermal loads, ensuring a rigorous comparative analysis of smart glazing technologies. The extreme summer temperatures and high solar radiation in Riyadh make it an ideal environment for evaluating the effectiveness of smart

glazing systems in mitigating solar heat gains and improving indoor thermal and visual comfort.

3.4.4.1 Simulation Parameters and Environmental Inputs

All simulations were configured to run over an annual period from January 1st to December 31st, 2024, with a timestep of 30 minutes (2 per hour). Table 11 summarizes the general simulation parameters, daylighting thresholds, control settings, and occupant-related environmental inputs applied in all scenarios.

Table 11: Simulation parameters and controls

Category	Parameter	Value
General simulation settings	Software	DesignBuilder v7.3.0.40
	Simulation engine	- EnergyPlus (Energy and Thermal) - Radiance (Visual and Daylighting)
	Simulation period	Jan 1 – Dec 31, 2024
	Timestep	2 per hour
	Simulation location	Riyadh, Saudi Arabia
	Simulation weather data	SAU Riyadh, TMY (2007-21) Latitude: 24.72° Longitude: 46.73°
	Temperature control	Air temperature
Lighting control	Lighting control type	Linear
	Target illuminance level	500 lux
	Working plane height	0.7 m
	% Zone controlled by sensor	100% (Lighting Area 1 only)
	Glare index threshold	22
Daylighting analysis	Analysis type	Annual and Point-in-Time
	Analysis date/time (for Point-in-Time)	21 September, 9:00 AM
	Climate/sky model	Perez all weather
	Direct Normal & Horizontal illuminance	1000 lux
	Daylight thresholds	sDA: 300 lux, UDI: 100–3000 lux
	Grid size	Min: 0.05 m, Max: 0.2 m
Thermal comfort inputs	Activity type	Light office work (standing/walking)
	Metabolic rate (Met)	0.9
	Clothing insulation (Clo)	Summer: 0.5, Winter: 1.0
	Summer months	June, July, August

3.4.4.2 Lighting Control and Sensor Placement

Lighting control was enabled for all occupied zones with visual access to daylight to reduce artificial lighting demand and improve visual comfort. A linear lighting control strategy was adopted, allowing electric lighting to dim continuously in response to increasing daylight availability. As daylight illuminance levels rise, electric lights dim linearly from maximum power and brightness to a defined minimum. Once the minimum dimming point is reached, the system maintains minimum power and light output regardless of further daylight increases [123]. This approach optimizes lighting energy consumption while maintaining consistent indoor illuminance levels.

Each zone was assigned a single lighting area, with 100% of the lighting load controlled by the first (main) lighting sensor. The sensor was placed automatically at the geometric center (x, y) of the zone, which is the default setting in DesignBuilder for representative daylight readings. The vertical position (z) of the sensor was defined by the working plane height of 0.7 meters, consistent with standard office desk height.

Zones without external windows or with insufficient daylight access (e.g., corridors or mechanical rooms) were excluded from daylight control, by DesignBuilder recommendations to avoid simulation errors. Additionally, the ground, mezzanine, and eighth floors were excluded due to either their unoccupied status or obstructed glazing conditions. The distribution of lighting sensors and daylight control across relevant floors and zones is summarized in *Table 12*.

Table 12: Floors and zones with active lighting control and sensor placement

Floor	Zones	Label	Occupancy	Light Control	Sensor location (x, y, z)
Second	Zone-1	Office	Occupied	ON	x,y: Geometric centre z: Working plane = 0.7 m
Third	Zone-2	Office	Occupied		
Forth	Zone-3	Office	Occupied		
Sixth	Zone-4	Office	Occupied		
Seventh	Zone-5	Corridor	Occupied		
Fifth	Zone-1	Corridor	Occupied		
	Zone-3	Office	Occupied		

3.4.4.3 Integration of Smart Glazing Systems

The integration of smart glazing systems into the simulation model was conducted to evaluate their thermal, visual, and daylighting performance within a controlled and consistent framework. The selected glazing technologies summarized in *Table 7* were implemented using the following approach:

- **Electrochromic (EC) and Thermochromic (TC)** glazing systems were directly imported from the EnergyPlus material library available within DesignBuilder. These entries provided validated optical and thermal performance data for commercially available products, ensuring the reliability of simulation inputs.
- **The remaining alternatives e.g.,** Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Gasochromic (GC), Photochromic (PC), and Thermotropic (TT), GG were not present in the EnergyPlus database. For these technologies, key material properties such as Solar Heat Gain Coefficient (SHGC), U-values, and Visible Light Transmittance (VLT) were collected from peer-reviewed literature, technical datasheets, and manufacturer documentation. These values were then manually entered into DesignBuilder to model each system's performance as realistically as possible.

- To streamline simulation management and data organization, each glazing alternative was assigned a unique identifier (e.g., A1 for PDLC, A7 for EC), corresponding to their entry in Table 7.
- All smart glazing systems were simulated in their static state, corresponding to either the darkest tint level or fully opaque condition.

3.4.4.4 Simulation Scenarios and Workflow

To maintain a systematic and unbiased evaluation, each glazing alternative was tested under identical conditions, allowing for direct performance comparisons. **A total of eight simulation scenarios** were conducted:

- **Seven** scenarios incorporating different smart glazing alternatives.
- **One** baseline scenario representing the 6mm clear single-glazed system for comparative analysis of energy saving, cost saving, and CO₂ mitigation assessment.

The simulation process followed a structured workflow to ensure a standardized evaluation of all smart glazing alternatives under comparable conditions:

1. **Baseline model setup:** The existing glazing system was modelled and calibrated as a reference case.
2. **Integration of smart glazing systems:** Each glazing alternative was implemented into the model while maintaining uniform building geometry, internal loads, and HVAC settings.
3. **Simulation runs:** The model was simulated on an hourly time step over a full annual cycle (Jan-2024 to December-2024), allowing for detailed assessment of energy, thermal, visual, and daylighting variations across different seasons.
4. **Data extraction:** Energy performance, daylighting, visual, and thermal comfort metrics were extracted from the simulation results.
5. **Post-processing of results:** Raw simulation outputs were converted into performance values corresponding to each sub-criterion.

6. **Simulation convergence:** Each scenario was iterated until the simulation results reached convergence, ensuring stability and accuracy in performance predictions.

3.4.5 Assessment of Environmental Performance

The environmental performance of smart glazing alternatives was assessed using energy efficiency metrics obtained through static-state simulations in DesignBuilder v7.3.0.40, a validated building energy simulation software. The simulations employed a calibrated case study model of a non-domestic office building situated in Riyadh, Saudi Arabia, representing typical hot-arid climatic conditions prevalent in the region.

To ensure consistency and accuracy, the simulation environment was configured according to parameters detailed in Section 3.7.4. The assessment followed a standardized approach, where:

- A single-glazed 6 mm clear glass system was established as the reference baseline for comparative analysis.
- Each smart glazing alternative was modeled separately, maintaining identical building operational conditions, including HVAC settings, internal loads, and occupancy schedules.
- The Riyadh EPW (EnergyPlus Weather) file was utilized to ensure an accurate representation of the local hot-arid microclimatic conditions.

Furthermore, to facilitate an objective, transparent, and comprehensive evaluation, the extracted performance metrics were systematically analyzed, normalized, and integrated into a structured multi-criteria decision matrix to enable robust comparative assessment.

3.4.5.1 Energy Efficiency (En-1)

Energy efficiency is a fundamental criterion in evaluating the environmental sustainability performance of smart glazing alternatives. This section outlines the methodology adopted

to quantify energy performance, focusing on energy consumptions, energy savings, and associated CO₂ emissions. The evaluation ensures a systematic and standardized approach to analyzing the impact of glazing alternatives through static simulations.

To comprehensively assess energy efficiency, the following sub-criteria were selected:

1. Electricity consumption for heating (En-1.1)
2. Electricity consumption for cooling (En-1.2)
3. Electricity consumption for artificial lighting (En-1.3)
4. Total energy consumption (Heating, Cooling, Lighting) (En-1.4)
5. Total energy savings relative to the baseline (En-1.5)
6. CO₂ mitigation potential (En-1.6)

a) Electricity Consumption for Heating, Cooling, and Artificial Lighting (En-1.1, En-1.2, En-1.3)

The electricity consumption for heating, cooling, and artificial lighting was directly extracted from the DesignBuilder simulation results in kWh/year for each glazing alternative.

b) Total Energy Consumption (En-1.4)

The total energy consumption was calculated as the aggregate energy demand for heating, cooling, and artificial lighting, using the following formula:

$$\textbf{Total Energy Consumption} = (\textbf{En} - \textbf{1.1}) + (\textbf{En} - \textbf{1.2}) + (\textbf{En} - \textbf{1.3}) \quad (5)$$

Where,

- **En-1.1:** Electricity consumption for heating
- **En-1.2:** Electricity consumption for cooling
- **En-1.3:** Electricity consumption for artificial lighting

This value represents the cumulative energy demand of the building for each smart glazing alternative. Heating, cooling, and lighting were specifically selected as these energy demands are directly influenced by smart glazing technologies,

c) Total Energy Savings (En-1.5)

The total energy savings for each smart glazing alternative were computed relative to the base case (BC) scenario using the following equation:

$$\text{Energy savings (KWh)} = \text{Energy Consumption (Base Case)} - \text{Energy Consumption (Smart Glazing Alternative)} \quad (6)$$

Percentage energy savings were calculated as:

$$\text{Energy savings (\%)} = \frac{\text{Energy savings (KWh)}}{\text{Energy Consumption (Base Case)}} \times 100 \quad (7)$$

This percentage indicates the relative improvement in energy efficiency achieved through the implementation of smart glazing solutions. The computed energy savings reflect both the increase in lighting energy consumption and the substantial reduction in cooling energy resulting from smart glazing integration.

d) CO₂ Mitigation (En-1.6)

Annual CO₂ mitigation was calculated based on the total energy savings (kWh), specifically considering energy consumption reductions in heating, cooling, and lighting. The calculation used is as follows:

$$\text{CO}_2 \text{ mitigation (kgCO}_2\text{)} = (\text{Total energy savings (KWh)}) \times (\text{CO}_2 \text{ emission factor}) \quad (8)$$

Where,

- **Total energy savings (kWh):** Energy saved relative to the baseline scenario.
- **CO₂ emission factor:** 0.5059 kgCO₂/kWh, specific to the electricity grid in Saudi Arabia. [124]

The emission factor (0.5059 kgCO₂/kWh) was sourced from the Climate Transparency Report (2021) and accounts solely for carbon dioxide emissions, excluding other greenhouse gases (GHGs) [124]. This metric clearly illustrates the environmental benefit achieved by implementing smart glazing alternatives, measured through reductions in carbon footprint.

3.4.6 Assessment of Social Performance

Social performance assessment in this study encompasses three key aspects: Visual Comfort & Daylighting, Thermal Comfort, and Acoustic Comfort. These criteria were selected due to their significant impact on occupant well-being and indoor environmental quality in non-domestic buildings. The assessment methodology was designed to facilitate a systematic and quantitative evaluation of each smart glazing alternative, utilizing simulations conducted in DesignBuilder v7.3.0.40 for Visual Comfort & Daylighting and Thermal Comfort.

Performance metrics were derived and assessed for seven smart glazing alternatives: Electrochromic (EC), Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Thermochromic (TC), Thermotropic (TT), Photochromic (PC), and Gasochromic (GC). These were benchmarked against a 6 mm single clear glass base case to ensure a comprehensive comparison, allowing for an in-depth evaluation of each alternative's performance. Furthermore, to facilitate an objective, transparent, and comprehensive evaluation, the extracted performance metrics were systematically analyzed, normalized, and integrated into a structured multi-criteria decision matrix to enable robust comparative assessment.

3.4.6.1 Visual Comfort and Daylighting Performance (Soc-1)

Visual comfort and daylighting play a critical role in assessing the social sustainability of smart glazing alternatives. This section details the methodology used to evaluate visual comfort and daylighting metrics, ensuring a structured and standardized approach to analyzing their impact through daylight simulations.

The Visual comfort and daylighting performance of smart glazing alternatives were assessed using the daylighting module of **DesignBuilder v7.3.0.40**, incorporating both **Annual and Point-in-Time analysis**. These simulations provide a comprehensive evaluation of **visual comfort and daylighting metrics**, ensuring consistency and comparability across different smart glazing.

Table 13 summarizes the key parameters and thresholds used for daylighting analysis. These simulation parameters were selected to ensure consistency and comparability across all glazing alternatives. The selected date (September 21) represents the autumn equinox, ensuring balanced daylight conditions. The UDI and sDA thresholds align with industry standards for daylighting analysis, ensuring robust visual comfort assessment.

Moreover, despite Riyadh's predominantly sunny climate, an overcast sky condition was used for daylight simulations to ensure a standardized and conservative evaluation approach. This choice aligns with internationally recognized daylight assessment standards (e.g., CIE Standard Overcast Sky), enabling robust benchmarking, effective glare and uniformity assessment, and ensuring adequate daylight availability under worst-case scenarios, thus enhancing the reliability and resilience of the daylight design strategy.

Table 13: Daylighting simulation parameters

Category	Parameter	Value
General Simulation Settings	Software	DesignBuilder v7.3.0.40 (Daylighting module)
	Simulation engine & Analysis type	Radiance (Annual & Point-in-Time analysis)
	Analysis date & time	September 21 / 9:00 AM
	Lighting control	ON (Adjusted based on daylight availability)
Lighting Control	Control type	Linear
	Target illuminance level	500 lux
	Maximum allowable glare index	22
	Sensors	
Shading & Sky Conditions	Shading control	No shading (Baseline assessment)
	Climate/sky model	Perez all weather
	Direct Normal & Horizontal illuminance	1000 lux
	sDA (Spatial Daylight Autonomy) lower threshold	300 lux
Daylighting Thresholds	sDA percentage annual hours	50%
	UDI (Useful Daylight Illuminance) threshold	100 - 3000 lux
	UDI percentage annual hours	50%
Simulation Grid & Calculation	Working plane height	0.7 m
	Grid size	Min: 0.05 m, Max: 0.2 m

To comprehensively assess visual comfort and daylighting performance of the smart glazing alternatives, the following sub-criteria were selected and assessed:

- Visible Light Transmittance (VLT) (Soc-1.1)
- Daylight Glare Index (DGI) (Soc-1.2)
- Daylight Autonomy (DA) (Soc-1.3)
- Uniformity of Daylight Illuminance (Soc-1.5)
- Useful Daylight Illuminance (UDI) (Soc-1.6)
- Daylight Factor (Soc-1.4)

a) Visible Light Transmittance (VLT) (Soc-1.1)

The Visible Light Transmittance (VLT) for each glazing system was sourced from manufacturer datasheets and DesignBuilder's glazing property databases, providing essential information on the amount of daylight entering interior spaces.

b) Daylight Glare Index (DGI) (Soc-1.2)

Glare is a critical factor in the evaluation of visual comfort within buildings. It is defined as a condition of vision caused by excessive luminance or extreme luminance contrasts within the field of view, leading to irritation, discomfort, or a reduction in visual performance. The Daylight Glare Index (DGI), a numerical scale, is specifically employed to predict the likelihood of discomfort due to daylight in indoor environments [125, 126]. The threshold values used for DGI in this study are summarized in *Table 14* [125].

Table 14: Glare classification based on the Daylight Glare Index (DGI) scale [125]

Glare Characterization	DGI
Intolerable	> 28
Just intolerable	28
Uncomfortable	26
Just uncomfortable	24
Acceptable	22
Just acceptable	20
Perceptible	18
Just imperceptible	≤ 16

In this study, DGI values for each smart glazing alternative were derived from DesignBuilder simulation outputs across all occupied floors and zones as mentioned in Table 12. For this study, the maximum allowable discomfort glare index was set at a DGI value of 22, aligning with recommendations provided by DesignBuilder [123].

A systematic approach was implemented to ensure consistent and representative DGI assessment across various smart glazing alternatives:

- **Simulation Data Extraction**

DGI values were derived from DesignBuilder simulation outputs across all occupied floors and zones.

- **Identification of Representative Zone**

To enable an objective comparative analysis, the floor and zone exhibiting the highest average DGI were identified. This representative reference case was established as Floor 7, Zone 4, selected due to its consistently higher glare conditions relative to other zones analyzed.

- **Selection of Peak Glare Period**

The month of **June** was chosen for data inclusion in the decision matrix, as simulations indicated this month consistently exhibited peak glare conditions among all analyzed months. This peak period represents typical worst-case summer glare scenarios, ensuring robust comparison and evaluation of smart glazing performance in terms of glare mitigation.

c) Daylight Autonomy (DA) (Soc-1.3)

In this study, Spatial Daylight Autonomy (sDA_{300lx}) was evaluated following the daylighting criteria established by the Leadership in Energy and Environmental Design (LEED v4.1) rating system. sDA_{300lx} quantifies how often daylight alone provides at least **300 lux** illuminance on the working plane (0.7 m height). Specifically, sDA represents the percentage of occupied hours throughout the year during which this minimum illuminance threshold is met by natural daylight [127, 128]. LEED v4.1 considers sDA_{300lx} as a key

metric, awarding up to three points based on performance thresholds: 1 point for $sDA \geq 40\%$, 2 points for $sDA \geq 55\%$, and 3 points for $sDA \geq 75\%$ (Table 15).

Table 15: sDA300lx rating criteria based on LEED4.1

sDA_{300lx} (%)	LEED4.1 Version
$sDA_{300lx} \geq 40$	1 point
$sDA_{300lx} \geq 55$	2 points
$sDA_{300lx} \geq 75$	3 points

The simulations were conducted using DesignBuilder, where sDA_{300lx} values were calculated for each individual zone. The final performance indicator was determined through an area-weighted average approach, computed using the following equation:

$$DA_{avg} (\%) = \frac{\sum_{i=1}^n (sDA_i \times A_i)}{\sum_{i=1}^n A_i} \quad (9)$$

Where:

- sDA_i : Spatial Daylight Autonomy (%) for zone i
- A_i : Floor area of zone i
- n : Total number of zones evaluated

d) Useful Daylight Illuminance (UDI) (Soc-1.6)

The useful daylight illuminance (UDI) has been widely used to evaluate the daylighting availability while considering visual comfort [129]. Useful Daylight Illuminance (UDI) evaluates annual daylight illuminance distributions across the working plane (0.7 m height), defining illuminance levels considered beneficial or "useful" by occupants. It excludes periods when daylight illuminance is insufficient or excessively high, as these conditions typically cause visual discomfort or glare. Specifically, UDI categorizes hourly illuminance values into distinct ranges, typically: 0–100 lux (insufficient), 100–2000 lux (useful), and above 2000 lux (excessive) [127, 128]. However, in this study, the upper

threshold of the useful range was set at 3000 lux, thus defining the useful illuminance range as 100–3000 lux.

The UDI Area in Range (%) for each zone was directly extracted from DesignBuilder simulation results, representing the percentage of each zone's floor area that achieves illuminance levels within the predefined useful range (100–3000 lux) during occupied hours.

For comparative evaluation within the decision matrix, an area-weighted average UDI across all zones was calculated as follows:

$$UDI_{avg} (\%) = \frac{\sum_{i=1}^n (sUDI_i \times A_i)}{\sum_{i=1}^n A_i} \quad (10)$$

Where:

- $sUDI_i$: UDI Area in Range (%) for zone i
- A_i : Floor area of zone i
- n : Total number of zones evaluated

e) Daylight Factor (Soc-1.4)

In design builder Daylight factor (DF) is determined/calculated as the ratio of indoor illuminance at a given point on the working plane (0.7 m above the floor) to the simultaneous outdoor illuminance measured on an unobstructed horizontal plane for overcast sky conditions, typically calculated across a grid of points within a zone [127].

In this study, the Average DF for each zone was directly extracted from DesignBuilder simulation results. The Average DF is calculated as the area-weighted average illuminance across the gridded working plane of each zone [127]. A single value (DF_{avg}) defines the performance of a zone. According to established criteria, a zone is considered adequately daylit if [127, 130]:

- The average daylight factor is at least **2.0%**, and
- The uniformity ratio is at least 0.4, or the minimum point daylight factor is at least 0.8%

For inclusion in the decision matrix, the area-weighted average DF across all evaluated zones was calculated as follows:

$$DF_{avg} (\%) = \frac{\sum_{i=1}^n (sDF_i \times A_i)}{\sum_{i=1}^n A_i} \quad (11)$$

Where:

- sDF_i : Average daylight factor (%) for zone i
- A_i : Floor area of zone i
- n : Total number of zones evaluated

f) Uniformity of Daylight (Soc-1.5)

Uniformity of daylight factor (UDF) or the daylighting uniformity ratio is the ratio between the minimum DF and average DF on the on the working plane within a room/zone [131]. It represents the consistency of daylight distribution across a zone.

In this study, UDF values for each zone were extracted directly from DesignBuilder simulation results. For inclusion in the decision matrix and to ensure a representative comparison across zones, an area-weighted average uniformity ratio was calculated as follows:

$$UDF_{avg} (\%) = \frac{\sum_{i=1}^n (sU_i \times A_i)}{\sum_{i=1}^n A_i} \quad (12)$$

Where:

- UDF_i : Uniformity ratio (Min/Avg) for zone i
- A_i : Floor area of zone i
- n : Total number of zones evaluated

3.4.6.2 Thermal Comfort (S-2)

This section outlines the structured methodology used to evaluate thermal comfort performance for smart glazing alternatives. Annual simulations were conducted using DesignBuilder v7.3.0.40, employing standardized parameters to ensure consistent, reliable, and comparable results across all glazing alternatives. The environmental parameters used reflect typical office occupancy conditions, summarized clearly in Table 16.

Table 16: Environmental input parameters for thermal comfort analysis

Category	Parameter	Value
General simulation settings	Software	DesignBuilder v7.3.0.40
	Thermal simulation engine	EnergyPlus
	Simulation period	Jan 1 – Dec 31, 2024
	Timestep	2 per hour
	Simulation location	Riyadh, Saudi Arabia
	Simulation weather data	SAU Riyadh, TMY (2007-21) Latitude: 24.72° Longitude: 46.73°
	Temperature control	Air temperature
	Activity type	Light office work (standing/walking)
	Metabolic rate (Met)	0.9 Met
	Clothing insulation (Clo)	Summer: 0.5 Clo Winter: 1.0 Clo
Thermal comfort inputs	Air velocity	0.137 m/s (DesignBuilder default for comfort calculations)
	Comfort radiant temperature weighting	Zone averaged
	Summer months (for decision matrix)	June, July, August

To comprehensively assess thermal comfort of the smart glazing alternatives, the following sub-criteria were selected and assessed:

- Solar heat gain coefficient (SHGC) (S2.1)
- U-Value glazing (S-2.2)

- Predicted Mean Vote (PMV) (S-2.3)
- Predicted Percentage of Dissatisfied (PPD) (S-2.4)
- Annual window heat gain (S-2.5)
- Indoor temperature (S-2.6)
- Light-to-solar gain ratio (LSG) glazing (S-2.6)

a) Solar Heat Gain Coefficient (SHGC) (S2.1)

The **Solar Heat Gain Coefficient (SHGC)** represents the fraction of incident solar radiation transmitted through glazing, including both directly transmitted solar radiation and absorbed solar energy re-emitted inwardly [132]. SHGC values range from 0 to 1, where higher values allow more solar heat gain and are generally suitable for colder climates to aid passive heating, while lower values are preferred in hotter climates to reduce cooling loads and improve thermal comfort [133].

SHGC values for each glazing alternative were sourced directly from the glazing material properties provided in Table 5 or extracted from DesignBuilder's glazing database.

b) U-Value Glazing (S-2.2)

The U-value, also known as the “overall heat transfer coefficient”, quantifies the rate at which heat passes through a building element per unit area per degree of temperature difference ($\text{W}/\text{m}^2\cdot\text{K}$). In the context of glazing systems, it measures the non-solar heat transfer through the glass due to conduction, convection, and radiation. Lower U-values indicate better thermal insulation and reduced heat flow, contributing to improved energy efficiency and thermal comfort [134, 135]

In this study, only the glazing portion of the window is considered for U-value evaluation. Frame, spacer, and seal effects are excluded. U-values for each glazing system were

obtained from Table 7 or extracted directly from DesignBuilder's glazing material properties database.

c) Predicted Mean Vote (PMV) (S-2.3)

The Predicted Mean Vote (PMV) predicts the average thermal sensation votes of occupants within a given environment [136]. PMV index assesses occupants' thermal comfort by incorporating air temperature, mean radiant temperature, relative humidity, air velocity, clothing insulation, and metabolic rate [133].

For commercial office buildings, European Standard EN ISO 7730 identifies three thermal comfort categories (Table 17) [136]. Several studies recommended Category B for office buildings due to its practical balance between comfort and feasibility. This category allows a PPD of less than 10%, corresponding to a PMV range of -0.5 to $+0.5$, representing an environment comfortable for most occupants.

Table 17: Categories of thermal environments according to ISO 7730 [136]

Category	PMV Range	Temperature Range (°C) for a Typical Office in Summer	PPD (%)
A	$-0.2 < \text{PMV} < +0.2$	24.5 ± 1	<6
B	$-0.5 < \text{PMV} < +0.5$	24.5 ± 1.5	<10
C	$-0.7 < \text{PMV} < +0.7$	24.5 ± 2.5	<15

For this research, PMV values were determined using simulations conducted in DesignBuilder software, which applies Fanger's PMV calculations consistent with ISO 7730 standards [137]. Monthly PMV values were extracted from simulation outputs, with specific emphasis on summer months (June, July, and August) to align with the climatic conditions pertinent to Riyadh. The average PMV of these summer months was computed

and integrated into the decision matrix for comparative evaluation of smart glazing performance.

d) Predicted Percentage of Dissatisfied (PPD) (S-2.4)

The Predicted Percentage of Dissatisfied (PPD) provides a quantitative estimation of the percentage of occupants expected to experience thermal discomfort, either too warm or too cool, in a given indoor environment [136]. PPD values were calculated using DesignBuilder software based on Fanger's equations as detailed in ISO 7730 [138]. Similar to PMV, monthly average values were obtained from the simulation results, and the summer months (June, July, and August) average was employed in the decision matrix to evaluate the thermal comfort performance of various smart glazing alternatives effectively.

e) Annual Window Heat Gain (S-2.5)

Annual window heat gain refers to the total short-wave solar radiation transmitted through external windows, which contributes significantly to the thermal loads in buildings. This metric was obtained directly from DesignBuilder simulations, measured in kilowatt-hours (kWh) [111].

f) Indoor Temperature (S-2.6)

Indoor thermal comfort also heavily relies on operative temperature, defined as the mean of the internal air and radiant temperatures within a space [137].

Similar to PMV and PPD, monthly average values were obtained from the simulation results, and the summer months (June, July, and August) average was employed in the decision matrix to evaluate the thermal comfort performance of various smart glazing alternatives effectively.

g) Light-to-Solar Gain Ratio (LSG) (S-2.6)

The Light-to-Solar Gain Ratio (LSG) evaluates glazing performance by balancing visible light transmittance (VLT) against solar heat gain coefficient (SHGC). It is calculated as follows:

$$\text{LSG}(\%) = \frac{\text{Visible Light Transmittance (VLT)}}{\text{Solar Heat Gain coefficient (SHGC)}} \quad (13)$$

Values of VLT and SHGC utilized in this calculation were sourced from Table 5.

3.4.6.3 Acoustic Comfort (Soc-3)

Acoustic comfort significantly influences occupants' satisfaction, health, and productivity within built environments. This section outlines the methodological approach employed to assess the acoustic performance of smart glazing alternatives by evaluating their Sound Transmission Class (STC) values.

a) Sound Transmission Class (STC) (Soc-3.1)

The Sound Transmission Class (STC) is a standardized rating that quantifies how well a building material, such as glass, reduces airborne sound transmission [139]. It is a single-number rating used in architectural applications, including windows, partitions, and facades, to assess noise insulation efficiency [140]. The STC value is determined by analyzing sound transmission loss (STL) across multiple frequencies and aligning it with a standardized reference curve [139, 140]. A higher STC value corresponds to improved sound insulation performance [139].

• Factors Affecting STC in Glazing Systems

The STC value of glazing systems is primarily influenced by the following factors:

- **Glass Type and Configuration:** Different types of glass, such as monolithic, laminated, tempered, and frosted, have varying STC values. However, research suggests that these differences are generally minimal, with variations of only 1-2 STC points. The glazing configuration (single, double, or triple layers) significantly influences STC ratings, as multi-layered glazing improves sound insulation by increasing mass and damping properties.[139, 141]
- **Glass Thickness:** Thicker glass typically achieves a higher STC rating since it provides greater resistance to airborne sound waves. In accordance with **mass law**, increasing the glass thickness enhances its sound insulation performance, with 10 mm monolithic glass offering better noise reduction than 6 mm monolithic glass. [141]
- **Glass Density:** The density of the glass material plays a key role in determining STC values. Higher-density glass absorbs and weakens sound waves more effectively, reducing noise transmission.[139]
- **Air Gap Between Glass Panes:** In double-glazed systems, wider air gaps improve sound insulation by disrupting direct sound wave transmission. [142]
- **Sealing Mechanisms:** Airtight seals and gaskets enhance sound insulation by preventing air gaps around the edges of glazing panels, reducing sound leakage. [142]

Hence, the STC value of glazing is influenced by mass, stiffness, and airtightness. Additionally, factors such as tint, glass coatings (low-e, reflective), and tempering processes do not significantly impact the STC ratings of glass [143]. To evaluate the STC values of smart glazing, this study considers these factors, focusing on three key parameters: glazing type, configuration, and thickness, as discussed further.

- **Rationale for Evaluating STC Values for Smart Glazing Alternatives**

While smart glazing technologies are primarily evaluated for their optical and thermal properties, there is limited research available on their acoustic performance. Given the lack of direct STC values for most smart glazing alternatives, this study estimates STC performance based on the following parameters:

- **Glass Type** (Monolithic or Laminated)
- **Glass Configuration** (Single-glazed, due to study constraints)
- **Glass Thickness** (Between 6 mm and 12 mm, as per reference data)

Since this study focuses exclusively on single-glazed systems, factors such as air gaps and airtight seals are not considered in the STC estimation. Additionally, tint, coatings, tempering, and glass positioning do not affect STC values and are therefore excluded from the analysis.

- **Selection Methodology for STC Values for Smart Glazing Alternatives**

A structured methodology was employed to determine the STC values for each smart glazing alternative. Reference acoustic data for single-glazed monolithic and laminated glass panels with thicknesses ranging from 6 mm to 12 mm were gathered from reputable sources, including peer-reviewed technical documents, manufacturer datasheets, and industry reports (Table 18). **The STC values were then derived from this data based on the closest match to each smart glazing alternative's type, thickness, and configuration.**

Table 18: Reference STC values (dB) for smart glazing alternatives

Suppliers		PC350 [144]	ZONA [145]	VIRACON [146]	FG Glass [143]	KSG Glass [147]	Dominant value
Glass Type	Thickness (mm/inch)	STC values					STC
Monolithic	6 mm (1/4")	32	31	31	31	31	31
	8 mm	–	–	–	32	–	32
	10 mm (3/8")	34	–	34	–	33	34
	12.4 mm (1/2")	–	36	36	36	–	36
	6 mm (1/4", 0.030" lamination)	35	35	35	35	–	35
Laminated	7.24 mm (1/4", 0.030" lamination)	–	35	–	–	–	35
	8 mm (5/16", 0.060" PVB lamination)	–	35	–	–	–	35
	9.53 mm (3/8", 0.030" lamination)	–	36	–	–	–	36
	9.76 mm (0.76 mm lamination)	–	–	–	36	–	36
	10 mm (3/8", 0.030" lamination)	35	–	36	–	–	36
	10.52 mm (3/8", 1.52 mm lamination)	–	37	–	37	–	37

3.4.7 Assessment of Economic Performance

Economic performance is a crucial factor in determining the financial feasibility and cost-effectiveness of smart glazing alternatives. Given the high initial investment associated with smart glazing technologies, a structured economic assessment was conducted to evaluate cost implications and potential long-term financial benefits.

Economic performance values for seven smart glazing alternatives; Electrochromic (EC), Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Thermochromic (TC), Thermotropic (TT), Photochromic (PC), and Gasochromic (GC) were obtained from combination resources like supplier quotes, manufacturer specifications, supplier websites, home services websites, relevant literature and simulation

results related to energy consumption. These alternatives were benchmarked against a 6 mm single clear glass baseline to enable comparative assessment.

Furthermore, to facilitate an objective, transparent, and comprehensive evaluation, the extracted performance metrics were systematically analyzed, normalized, and integrated into a structured multi-criteria decision matrix to enable robust comparative assessment.

3.4.7.1 Cost (Ec-1)

The economic assessment of smart glazing alternatives focuses on cost-related metrics, covering both initial investment costs and operational energy savings. The methodology follows a structured and standardized approach, ensuring that financial evaluations are reliable, transparent, and comparable across alternatives. The cost assessment is divided into the following sub-criteria:

- Initial Cost / Glazing Unit Cost (Ec-1.1)
- Cooling Cost Savings (Ec-1.2)
- Total Energy Cost Savings (Ec-1.3)
- Payback Period (PBP) (Eco-1.4)

a) Initial Cost / Glazing Unit Cost (Ec-1.1)

The initial cost per square meter of each smart glazing technology was determined through a combination of direct communication with manufacturers and suppliers, supplier quotes, manufacturer specifications, supplier websites, and home services databases. For R&D-stage smart glazing technologies, such as thermotropic and gasochromic glazing, cost estimates were derived through comparative analysis with commercially available technologies exhibiting similar functional characteristics. This approach ensured a realistic approximation of potential market costs for emerging smart glazing solutions.

However, it is important to acknowledge that the initial cost values considered in this study may not be universally applicable, as smart glazing costs are influenced by multiple external factors. These factors introduce variability in pricing, making it essential to consider context-specific conditions when assessing financial feasibility. Key factors affecting smart glazing costs include [148, 149]:

- **Glass size**

The cost of smart glazing increases proportionally with the size of the window or glass unit, as larger panels require more raw materials and advanced manufacturing processes.

- **Order quantity**

Larger bulk orders often lead to economies of scale, reducing the per-unit cost of smart glazing, whereas smaller orders may incur higher production and processing costs.

- **Application type**

Smart glazing systems that require electrical wiring, control systems, or automation as seen in electrochromic and suspended particle device (SPD) glazing, tend to have higher installation costs compared to passive smart glazing systems, such as thermotropic or gasochromic glazing.

- **Geographic location and delivery**

Suppliers may apply additional charges for delivery, depending on the location, order size, and shipping constraints.

- **Supplier and brand variation**

Different suppliers and brands offer varying pricing structures, warranties, and product quality standards. Premium brands may provide enhanced durability and superior performance, but at a higher cost, while lower-cost alternatives may lack proven long-term reliability.

- **Labour costs**

The cost of labour and installer availability varies by region. In areas where smart glazing installers are limited or specialized, installation costs may be higher due to increased demand and reduced competition.

These factors highlight the complexity of pricing smart glazing technologies, reinforcing the need for careful financial planning when considering their integration into non-domestic buildings in hot climatic regions.

b) Cooling Cost Savings (Ec-1.2)

As the study is conducted in a cooling-dominant climate, cooling energy cost savings were analysed separately in a hot climatic region. Annual cooling energy cost savings were computed based on simulation results of cooling consumption for each smart glazing system. These savings represent the difference in cooling energy consumption between the baseline case (6 mm single clear glass) and each smart glazing alternative. The cooling energy cost savings were calculated using the following formulas:

$$\text{Cooling energy savings (kWh/year)} = \text{Cooling energy Consumption (Base Case)} - \text{Cooling energy Consumption (Smart Glazing Alternative)} \quad (14)$$

$$\begin{aligned} \text{Cooling energy cost savings} \\ = \text{Cooling energy savings (kWh/year)} \times \text{Energy cost (USD/kWh)} \end{aligned} \quad (15)$$

The tariff for commercial buildings in Saudi Arabia was sourced from the **Saudi Electricity Company**, set at **USD 0.08/kWh (30 Halalah/kWh)** for commercial buildings with energy consumption of more than 6000 kWh [150].

c) Total Energy Cost Savings (Ec-1.3)

Total energy cost savings were derived by multiplying the annual energy savings (kWh/year) by the prevailing electricity tariff [151]. The tariff for commercial buildings in Saudi Arabia was sourced from the Saudi Electricity Company, set at USD 0.08/kWh (30 Halalah/kWh) for commercial buildings with energy consumption of more than 6000 kWh [150].

$$\begin{aligned} \text{Energy cost savings} & \quad (16) \\ &= \text{Total energy savings (kWh/year)} \times \text{Energy cost per kWh} \end{aligned}$$

d) Payback Period (PBP) (Eco-1.4)

The Payback Period (PBP) is a key financial metric that estimates the time required to recover the initial investment in smart glazing through operational cost savings. A shorter payback period indicates a financially viable investment, as it ensures quicker capital recovery.

The payback period was calculated using the following formula: [151]

$$\text{Payback period (PBP)} = \frac{\text{Initial investment}}{\text{Annual cost savings}} \quad (17)$$

3.4.8 Assessment of Technical Performance

The technical dimension of sustainability focuses on the long-term performance, quality, and service life of a building, system, or technology within the built environment [152]. While sustainability has traditionally been defined by its three core dimensions, environmental, social, and economic, certain technical aspects of smart glazing, such as durability, switching time, actuation type (active/passive), commercial maturity, and availability, are not directly related to any specific conventional dimensions. However,

these technical aspects play a crucial role in sustainability assessment and selection of smart glazing.

By incorporating technical sustainability into the assessment framework, this study ensures a comprehensive evaluation of smart glazing solutions, emphasizing their operational efficiency, durability, and market feasibility. To facilitate a systematic evaluation, this study relies on quantifiable technical performance criteria for the selected smart glazing alternatives; Electrochromic (EC), Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Thermochromic (TC), Thermotropic (TT), Photochromic (PC), and Gasochromic (GC), obtained from peer-reviewed literature and manufacturer databases, except for commercial maturity, which was assessed using a structured evaluation rubric.

To ensure objectivity, transparency, and comparability, the extracted technical performance metrics were systematically analyzed, normalized, and integrated into a structured multi-criteria decision matrix, allowing for a robust comparative assessment of smart glazing technologies.

3.4.8.1 Operational Performance (T-1)

Operational performance is a key criterion of technical sustainability, evaluating the functionality, responsiveness, efficiency, and durability of smart glazing technologies. In the context of smart glazing, operational performance refers to the system's ability to transition between states efficiently, maintain durability, have less dependence on energy for operation, and demonstrate commercial feasibility. Thus, the assessment of operational performance in this study is divided into the following sub-criteria:

- Switching time/Transition speed (T-1.1)
- Actuation (T-1.3)

- Power Requirement for Glazing State (T-1.4)
- Durability (T-1.5)
- Commercial maturity level (T-1.7)

a) Switching Time/Transition speed (T-1.1)

The switching time or transition speed of a smart glazing system refers to the time required for the glazing to change its optical properties (e.g., tinting or transparency level) in response to external stimulus. Faster switching times enhance occupant comfort by allowing instantaneous control over daylight and glare, while also contributing to energy optimization in highly glazed buildings [153]. The Performance values for switching time were extracted from relevant literature for each glazing type.

b) Actuation (T-1.3)

The actuation type of smart glazing defines whether the system is Active (requiring an external power source for activation) or Passive (self-regulating based on temperature, light, or chemical reactions). For this study, the actuation type of each smart glazing alternative was identified based on a literature review.

Since the actuation type is a categorical variable, a numerical ranking system was applied to facilitate its integration into the multi-criteria decision matrix.

c) Power Requirement for Glazing State (T-1.4)

The operational energy requirement measures the power consumption needed to switch or maintain states in smart glazing systems. Power consumption data were obtained from literature sources and manufacturer technical sheets.

d) Durability (T-1.5)

Durability assesses the lifespan, reliability, and material stability of smart glazing systems under prolonged exposure to UV, temperature fluctuations, and repeated switching cycles. A high durability score indicates a system that can withstand long-term operational conditions with minimal degradation, ensuring sustainability through reduced replacement frequency and maintenance costs. Durability values were extracted from peer-reviewed literature and technical reports.

e) Commercial Maturity Level (T-1.7)

Commercial maturity refers to the level of market availability, real-world adoption, and technological advancement of different smart glazing technologies. It indicates the degree to which a technology has progressed from research and development into practical, real-world applications. In the context of smart glazing technologies, commercial maturity is essential to ensure that the selected systems are not only technically advanced but also feasible for implementation in sustainable building projects. This ensures a balance between innovation and practicality, supporting both immediate application and long-term environmental benefits.

To systematically evaluate the commercial maturity of smart glazing systems, a structured rubric was developed as shown in Table 19. Notably, the Technology Readiness Level (TRL) retains its detailed 1–9 scale to preserve its authenticity, while other criteria use a simplified 1–5 scale for consistency.

Table 19: Rubric for commercial maturity evaluation

Assessment criteria	Description	Assessment scores				
		5 (Very High)	4 (High)	3 (Moderate)	2 (Low)	1 (Very Low)
TRL	Measures the development status, from basic research (TRL 1–3) to full-scale commercialization (TRL 9).	Fully commercialized (TRL 9)	Demonstration in real environments (TRL 7–8)	Pilot-scale validation (TRL 6)	Prototype development (TRL 4–5)	Research phase only (TRL 1–3)
Market presence	Assesses the availability of the technology in global markets and reviews the number and reliability of manufacturers offering the technology.	Widely available globally with many reliable suppliers	Available in major markets with multiple suppliers	Available in niche markets with few suppliers	Limited regional availability with one or two suppliers	Rarely available or experimental with no established suppliers
Adoption in projects	Examines real-world case studies, pilot projects, and commercial scale use in building applications.	Common in large-scale projects	Frequently adopted	Occasionally adopted	Rarely adopted	No real-world adoption
Cost competitiveness	Compares the cost-effectiveness of the technology relative to other smart glazing systems.	Highly competitive	Moderately competitive	High initial costs	Expensive, limited affordability	Prohibitively expensive/prototype only
Performance validation	Considers whether the technology has been validated through certifications, pilot studies, or projects.	Fully validated and certified	Partially validated	Some pilot studies	Limited validation	No validation or testing

3.5 Decision Model Development

The decision-making framework developed in this study integrates both subjective and objective weighting schemes within a TOPSIS-based Multi-Criteria Decision-Making (MCDM) model to identify the most sustainable smart glazing alternative for a non-domestic building in a hot climatic region. The methodological structure of the decision model is visually illustrated in Figure 21, while the corresponding procedures are elaborated below.

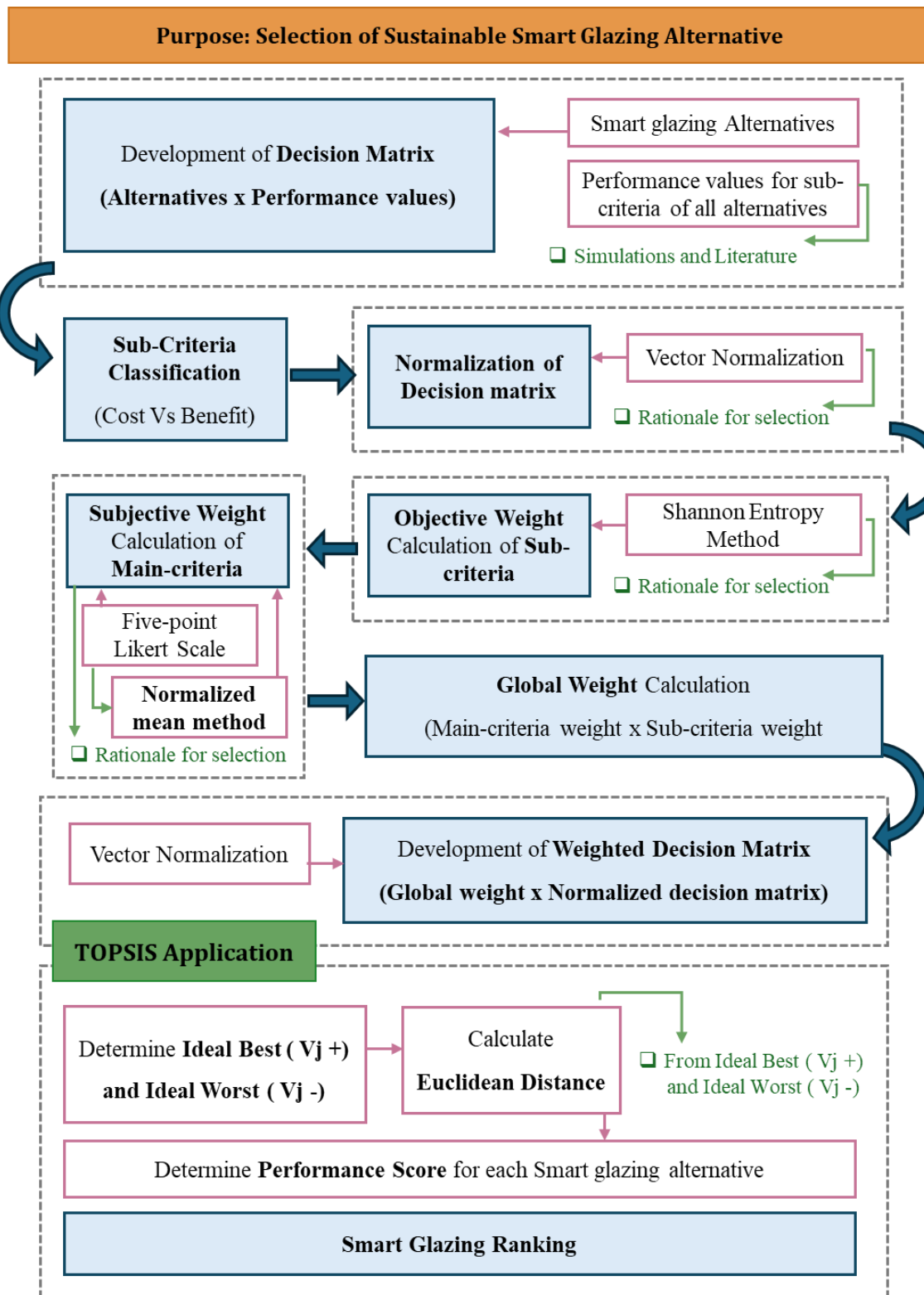


Figure 21: Methodological overview of decision model development

3.5.1 Development of Decision Matrix

A decision matrix $D = [P_{ij}]_{m \times n}$ was formulated, where P_{ij} represents the performance value of alternative A_i concerning the sustainability sub-criterion C_j .

The matrix structure includes smart glazing alternatives (A_n) evaluated across a comprehensive set of sub-criteria (C_m) drawn from environmental, economic, social, and technical sustainability dimensions. Performance data were gathered from a combination of simulations and a comprehensive literature review.

The decision matrix structure is as follows:

$$DM = \begin{matrix} & A_1 & A_2 & \dots & A_n \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} & \begin{bmatrix} P_{11} & P_{12} & \dots & P_{1n} \\ P_{21} & P_{22} & \dots & P_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ P_{m1} & P_{m2} & \dots & P_{m2} \end{bmatrix} \end{matrix} \quad (18)$$

Where,

- m : Number of sub-criteria
- n : Number of Smart glazing alternatives

3.5.2 Classification of Sub-Criteria

Each sub-criterion was first classified as either a **cost criterion** (where lower values are preferred) or a **benefit criterion** (where higher values are desired) [154]. This distinction is crucial for ensuring that all performance indicators are directionally aligned before normalization.

3.5.3 Normalization of Decision Matrix

Given the diversity of units and scales across sub-criteria, vector normalization was applied to convert the raw decision matrix into a dimensionless format suitable for further analysis.

The normalized value r_{ij} was calculated using the following formulas: [95]

- For benefit criteria

$$r_{ij} = \frac{P_{ij}}{\sqrt{\sum_{i=1}^m P_{ij}^2}} \quad (19)$$

- For cost criteria

$$r_{ij} = 1 - \frac{P_{ij}}{\sqrt{\sum_{i=1}^m P_{ij}^2}} \quad (20)$$

Where,

- r_{ij} : Normalized performance value
- P_{ij} : Raw performance value

Hence, the normalized decision matrix (NDM) for evaluation can be presented as follows:

$$NDM = \begin{matrix} & \begin{matrix} A_1 & A_2 & \dots & A_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} & \begin{bmatrix} r_{11} & r_{12} & \dots & r_{1n} \\ r_{21} & r_{22} & \dots & r_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ r_{m1} & r_{m2} & \dots & r_{mn} \end{bmatrix} \end{matrix} \quad (21)$$

• Rationale for Choosing Vector Normalization

Vector normalization was chosen for this study because it scales the criteria data to a common basis **without distorting the relative proportions or distribution of original values**. Each criterion's values are divided by their Euclidean norm, preserving the performance ratios between alternatives [155]. For instance, if alternative A has twice the value of alternative B before normalization, it will still have twice the value after normalization. This preservation of internal ratios ensures that the shape of the distribution remains unchanged, a property that is crucial for objective weighting techniques like entropy. Studies have shown that using vector (unit-length) normalization leaves the entropy-calculated weights essentially unaffected, whereas alternative methods such as min–max normalization may significantly alter the weight outcomes. [94]

Another reason for selecting vector normalization is that it avoids **artificial exaggeration or compression of performance differences**, which can occur when the raw data spans a wide numerical range. Methods like min–max normalization force all values between 0 and 1 by anchoring them to the minimum and maximum values, which can lead to **amplification or suppression of natural variation** within the dataset. As reported by Anes and Abreu (2025) [156], such rescaling can distort the perception of performance differences, particularly when criteria exhibit high variance. Vector normalization avoids this by applying a uniform scaling factor based on the norm of the data column, thereby preserving true performance relationships between alternatives.

This normalization method is particularly suited to this study, where the performance values are sourced from simulations and literature, and the priority is analytical accuracy rather than direct interpretability. Although normalizing to a 0–1 range (as in min–max) can make values more intuitive for presentation, the use of normalized data here is primarily for entropy weighting and TOPSIS computation, where preserving the fidelity of performance variation is more critical than visual simplicity. (*Figure 22*)

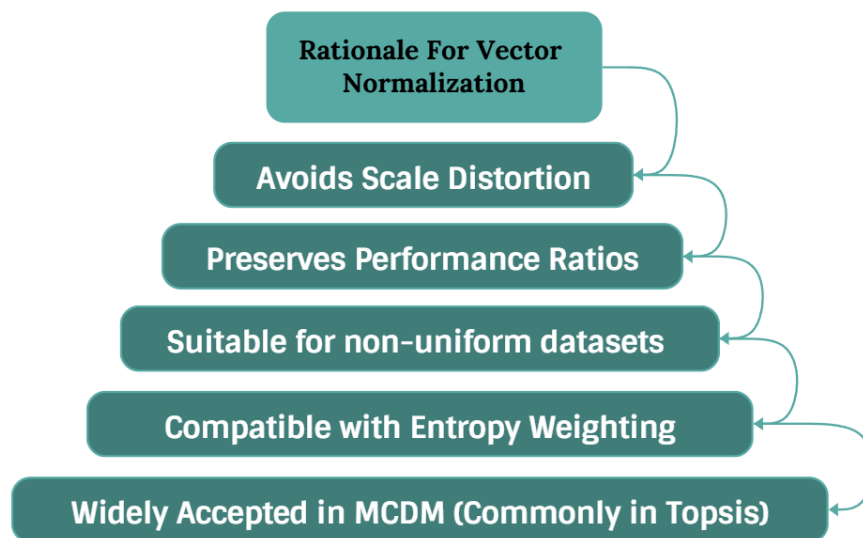


Figure 22: Rationale of vector normalization selection

3.5.4 Objective Weight Calculation for Sub-Criteria

To derive the objective weights for sub-criteria, the Shannon entropy method was employed. Entropy estimates the amount of information contained in the performance data for each sub-criterion based on its variability. Greater dispersion (i.e., more contrast between alternatives) implies higher informational value and thus, higher weight. [157]

To derive the objective weights for the sub-criteria using Shannon entropy, the following step-by-step procedure is applied: [157]

Step 1: The normalized decision matrix was used as input. (as outlined in Section 3.5.3).

Step 2: The Shannon entropy value E_j for each sub-criterion j , was computed using the formula:

$$E_j = -k \sum_{i=1}^m p_{ij} \times \log(p_{ij}) \quad (22)$$

Where,

- $p_{ij} = \frac{r_{ij}}{\sum_{i=1}^n (r_{ij})}$
- $k=1/\ln(m)$: Normalization constant that ensures the entropy value lies between 0 & 1
- m : Number of alternatives
- r_{ij} : Normalized performance values

Step-3: The degree of diversification $d_j=1 - E_j$ was calculated for each sub-criterion.

Step-4: The entropy weight w_j for each sub-criteria j was derived by normalizing the diversification values:

$$w_j = \frac{1 - E_j}{\sum_{i=1}^n (1 - E_j)} \quad (23)$$

This step yields a normalized weight w_j for sub criteria $j=1,2, 3...,n$, ensuring that $\sum w_j=1$.

The result reflects each criterion's degree of importance based on the dispersion of its values across alternatives.

- **Rationale**

The entropy method was selected for sub-criteria weighting due to the technical complexity, extensiveness, and specificity of the indicators used in this study, which are tightly related to the building energy and material performance of smart glazing systems. The highly specialized nature of these criteria makes it impractical to rely solely on expert judgment or surveys for accurate weighting, especially when pairwise comparisons would require significant time and effort, given the large number of sub-criteria.

Additionally, due to the niche topic of sustainable smart glazing in hot climates, it is challenging to gather a sufficiently large and diverse panel of experts familiar with all technical aspects of every sub-criterion. In this context, entropy weighting offers a robust, data-driven alternative that objectively determines weights based on the intrinsic variability within the decision matrix itself, eliminating subjective bias.

3.5.5 Subjective Weight Calculation for Main Criteria

For the main criteria under sustainability dimensions in this study, a subjective weighting approach is employed using a structured five-point Likert-scale survey. Respondents rated the importance of each sub-criterion using the five-point Likert scale ranging from 1 (Not Important) to 5 (Extremely Important). The detailed design and implementation of the survey are presented in the section 3.3. This section describes the methodology adopted to interpret and derive the weights from the survey responses.

To interpret the weights of main criteria from experts' responses, a **hierarchical normalized mean aggregation method** was applied. This method involves three main steps: [158]

Step 1: The arithmetic mean $\bar{x}_j$ was calculated for each sub-criterion j , and was calculated across all expert responses:

$$\bar{x}_j = \frac{1}{n} \sum_{i=1}^n (x_{ij}) \quad (24)$$

Where:

- x_{ij} : rating assigned by respondent i to sub-criterion j
- n : the number of respondents (22 in this case)

Step 2: The total importance score M_k for each main criterion k was computed by summing the mean scores of its corresponding sub-criteria:

$$M_k = \sum_{i \in C_k} (\bar{x}_j) \quad (25)$$

Where C_k is the set of sub-criteria under main criterion under k .

Step 3: The final weight W_k for each main criterion was calculated by normalizing its total score:

$$W_k = \frac{1}{\sum_{k=1}^k (M_k)} \quad (26)$$

Where:

- W_k : Weight of main criteria
- k : Total number of main criteria

• Rationale and Justification

Objective weighting techniques, such as the Shannon Entropy method, require measurable performance data, which is not available for abstract or strategic-level criteria like “Visual Comfort” or “Cost” in isolation. These main criteria serve as thematic categories and derive their meaning only through the performance of their sub-criteria. As such, subjective weighting via expert judgment was necessary and appropriate.

The normalized mean aggregation method provides a transparent and mathematically robust approach to converting Likert-scale-based ratings into a set of comparable, normalized weights. While prior studies [158], have applied this method in flat structures,

this study extends it to a hierarchical MCDM framework. This adaptation ensures that top-level sustainability dimensions reflect the combined perceived importance of their sub-criteria and respective categories (Main criteria), enabling meaningful integration into the overall decision model.

3.5.6 TOPSIS Application

Once the weights were established, the TOPSIS method was implemented to rank the smart glazing alternatives. TOPSIS compared each alternative's proximity to the ideal solution (best-case scenario) and its distance from the negative-ideal solution (worst-case scenario).

The TOPSIS method, originally proposed by Hwang and Yoon [159], involves identifying both a positive ideal solution and a negative ideal solution, and then computing the Euclidean distance of each alternative to these reference points. This allows the alternatives to be compared in terms of their relative closeness to the most preferred and least preferred outcomes. The method avoids the ambiguity that arises when evaluating performance based only on proximity to the best or worst solution. [160]

Hwang and Yoon [159] emphasized the critical role of normalization in the TOPSIS method, noting that it significantly influences the contribution of each attribute to the overall evaluation. To address this, the use of **vector normalization** was recommended to ensure consistent scaling across all criteria. In alignment with this guidance, vector normalization was adopted in the present study to maintain methodological consistency with both the entropy weighting process and the subsequent TOPSIS ranking procedure.

The process of implementing TOPSIS was conducted as follows [94, 159]:

Step 1: The normalized evaluation matrix was established using vector normalization (as described earlier section 3.5.3).

Step 2: The normalized values were then multiplied by their respective global weights to form the weighted normalized matrix. The global weight of each sub-criterion was calculated by multiplying its objective weight (obtained from the entropy method) by its corresponding main criterion weight (obtained from the Likert-scale survey). The weighted normalized matrix $V = [v_{ij}]$ was computed as:

$$v_{ij} = r_{ij} \times w_j^{global} \quad (27)$$

Hence, the weighted normalized decision matrix for evaluation can be presented as follows:

$$V = \begin{matrix} & \begin{matrix} A_1 & A_2 & \dots & A_n \end{matrix} \\ \begin{matrix} C_1 \\ C_2 \\ \vdots \\ C_m \end{matrix} & \begin{bmatrix} v_{11} & v_{12} & \dots & v_{1n} \\ v_{21} & v_{22} & \dots & v_{2n} \\ \vdots & \vdots & \ddots & \vdots \\ v_{m1} & v_{m2} & \dots & v_{m2} \end{bmatrix} \end{matrix} \quad (28)$$

Step 3: The positive ideal solution A^+ and the negative ideal solution A^- were determined. For benefit-type criteria, the maximum value represented the ideal best and the minimum value the ideal worst. For cost-type criteria, the opposite applied. The following formulations were used:

- For benefit criteria:
$$A_j^+ = \max(v_{ij}), \quad A_j^- = \min(v_{ij}) \quad (29)$$

- For cost criteria:
$$A_j^+ = \min(v_{ij}), \quad A_j^- = \max(v_{ij}) \quad (30)$$

Step 4: The Euclidean distance of each alternative from the positive ideal solution (A^+) and the **negative ideal solution** (A^-) denoted as S^+ and S^- , respectively, was calculated using the following expressions:

$$S_j^+ = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^+)^2} \quad (31)$$

$$S_j^- = \sqrt{\sum_{j=1}^n (v_{ij} - A_j^-)^2} \quad (32)$$

Step 5: The final performance score for each alternative, denoted as the relative proximity to the ideal solution (C_i^*), was determined using the following equation:

$$C_i^* = \frac{S_j^-}{S_j^+ + S_j^-} \quad (33)$$

Where:

- $C_i^* \in (0,1)$; values closer to 1 indicate stronger proximity to the ideal solution.

Step 6: Based on the calculated C_i^* values, the alternatives were ranked in descending order. Alternatives with higher C_i^* values were considered preferable, indicating better overall performance across the criteria evaluated.

• Rationale for Choosing TOPSIS

The decision to use TOPSIS for ranking the smart glazing solutions was made after considering alternative MCDM methods, and it was driven by several advantages of TOPSIS in the context of this study as given below:

- ✓ TOPSIS inherently accounts for both the best-case and worst-case performance scenarios by incorporating the ideal and negative-ideal reference points [161]. This means the selected glazing solution is not only excellent in approaching the desired ideals (e.g., high energy efficiency, low cost) but also prudent in avoiding the poorest outcomes on any criteria, thereby offering a balance in selection that is crucial for sustainable decision-making. Methods that only consider the best outcomes (like simple scoring or weighted sum models) might overlook how far an option is from a

disastrous performance on some criteria; TOPSIS ensures a more robust compromise by evaluating each alternative against the dual benchmarks of perfection and failure.

- ✓ TOPSIS offers ease of interpretation and computation. Its step-by-step procedure (normalization, weighting, distance calculation) is mathematically straightforward and can be easily programmed or executed in a spreadsheet, even for a large number of criteria. [94]
- ✓ TOPSIS has a proven track record in similar multi-criteria evaluations (including many sustainability technology selections), giving confidence in its reliability and acceptance in academic and industry circles. Overall, by using TOPSIS, the study leveraged a method that is theoretically sound, computationally efficient, and well-aligned with the decision objectives of balancing multiple sustainability criteria. These qualities made TOPSIS an appropriate and defensible choice for the smart glazing system selection in this study, compared to other ranking techniques that might not simultaneously offer the same level of insight into both optimality and risk (distance from worst) while remaining straightforward to apply. [94, 161]

CHAPTER 4

RESULTS AND DISCUSSION

This chapter presents the analysis and interpretation of results obtained throughout the multi-stage research process. It is organized according to the key methodological stages used in the development of the Sustainability Assessment Framework for Smart Glazing (SG-SAF). The discussion begins with the outcomes of the systematic literature review, where sustainability criteria and sub-criteria relevant to smart glazing technologies were identified. This is followed by the validation and prioritization of criteria through expert surveys, aimed at refining their relevance and applicability in the context of non-domestic buildings in hot climates.

Subsequent sections cover the collection and structuring of performance data, derived from simulations, literature, and manufacturer sources. The normalized data is then used to construct a decision matrix, followed by the application of weighting techniques and multi-criteria decision-making (MCDM) methods. The discussion integrates findings from each of these stages to provide a comprehensive view of how the SG-SAF supports the evaluation and selection of sustainable smart glazing alternatives.

4.1 Results of the Systematic Literature Review

This section presents the results from the systematic literature review conducted on 47 studies, aiming to fulfill the study's objective: "To systematically identify, categorize, analyze, and synthesize sustainability assessment criteria for smart glazing technologies, ensuring a comprehensive evaluation of environmental, economic, technical, and social dimensions tailored to sustainable building applications."

The review adhered to PRISMA guidelines and involved a thorough search through the Scopus database, using a broad set of keywords related to smart glazing technologies. The search initially spanned publications from January 1985 to November 2024 and was limited to peer-reviewed journal articles, conference papers, and reviews written in English. To maintain the focus and relevance of the review, specific inclusion and exclusion criteria (Table 4) were established. Studies included were those that focused on smart glazing technologies in non-domestic buildings across hot climates, assessing their performance in buildings. Exclusions were made to studies that did not meet these criteria. The initial search yielded 548 records, which were subjected to a two-step screening process based on titles, abstracts, and the set inclusion criteria. This process refined the selection to 138 articles of potential relevance. A subsequent full-text review assessed these articles for methodological rigor and alignment with the study's objectives, which further narrowed the field to 47 articles. Additionally, a snowballing technique was applied to the references of these articles to identify further studies, ensuring no relevant research was omitted. A PRISMA flow diagram (Figure 12) visually details this selection process, illustrating the methodical approach used to filter and select studies for final inclusion.

From these 47 studies, data was extracted to form the foundational basis for the subsequent objectives of the study, focusing on analyzing and developing sustainability assessment criteria for smart glazing technologies.

4.1.1 Bibliometric Overview of Selected Studies

Bibliographic information of the included studies, such as study titles, publication years, journals or conference proceedings, and their respective references, identified through the SLR, is presented in Table 20. Among the selected studies ($n = 47$), peer-reviewed journal

articles constitute the majority (n=45), complemented by one doctoral thesis and two conference papers. Notably, most of the identified studies were published in high-impact journals such as *Energy and Buildings*, *Journal of Building Engineering*, *Applied Energy*, *Journal of Cleaner Production*, and *Building and Environment*, underscoring the academic rigor and credibility of the reviewed literature.

Moreover, Figure 23 illustrated the temporal distribution of publications spans from 2008 to 2025, with a marked increase in output after 2020. The highest number of publications occurred in 2024, indicating a growing academic focus on the role of smart glazing in sustainable building design.

Table 20: Bibliometric characteristics of identified studies

Title	Year	Journal/Conference	Ref.
Assessing the Energy-Saving Potential and Visual Comfort of Electrochromic Smart Windows in Office Buildings: A Case Study in Dhahran, Saudi Arabia	2023	Sustainability	[162]
Assessment of the overall energy performance of an SPD smart window in a hot desert climate	2022	Energy	[116]
A multi-objective evaluation for envelope refurbishments with electrochromic glazing	2022	Results in Engineering	[163]
Life cycle cost analysis on three high-performance glazing systems for an office building in New Cairo, Egypt	2021	Architectural Engineering and Design Management	[24]
A comparative life cycle assessment of three high-performance glazing systems for office buildings in a hot desert climate zone	2020	Clean Technologies Environmental Policy	[20]
Polymer dispersed liquid crystal retrofitted smart switchable glazing: Energy saving, diurnal illumination, and CO2 mitigation prospective	2022	Journal of Cleaner Production	[164]
Active smart switchable glazing for smart city: A review	2024	Journal of Building Engineering	[67]
Ideal thermochromic smart window in a south-facing office room of China considering daylighting and energy performance	2023	International Journal of Green Energy	[165]
Electrochromic Windows: Return on Investment Analysis.	2022	Construction Management	[70]

Title	Year	Journal/Conference	Ref.
Applications of thermochromic and electrochromic smart windows: Materials to buildings.	2023	Cell Reports Physical Science	[17]
Assessing Visual and Non-Visual Daylighting Performance of Electrochromic Glazing Systems Based on User Centered Lighting Design. (PhD thesis)	2021	North Carolina State University: United States	[32]
Comparative energy and economic performance analysis of an electrochromic window and automated external venetian blind	2012	Energy Procedia	[166]
Assessment of Gel-Based Thermochromic Glazing for Energy Efficiency in Architectural Applications	2024	Materials	[167]
Experimental study on indoor thermal and daylighting performance of different thermotropic window systems in subtropical climate	2025	Energy and Buildings	[168]
Assessment of Gel-Based Thermochromic Glazing for Energy Efficiency in Architectural Applications	2024	Materials	[169]
Evaluation of colour properties due to switching behaviour of a PDLC glazing for adaptive building integration	2018	Renewable Energy	[170]
Thermal Comfort and Visual Comfort in an Office Building Equipped with Smart Electrochromic Glazing: An Experimental Study	2015	Energy Procedia	[171]
Solar-optical and thermal behavior of photochromic glazing: Small-scale testing under real sky conditions	2024	Construction and Building	[49]
Simulation-Based Evaluation of the Impact of an Electrochromic Glazing on the Energy Use and Indoor Comfort of an Office Room	2024	Energies	[172]
Annual evaluation of the visual-thermal comfort and energy performance of thermotropic glazing in a reference office room of China	2024	Building and Environment	[129]
Smart Glazing Systems vs Conventional Glazing: A Comprehensive Study on Temperature Control, Daylighting, and Sustainability	2024	International Journal of Sustainable Development and Planning	[173]
Solar responsive building glazing: Experimental analysis of the impact of photochromic glazing on indoor thermal and luminous conditions	2024	Journal of Building Engineering	[53]
Effect of smart glazing with electrochromic and thermochromic layers on building's energy efficiency and cost	2024	Energy and Buildings	[174]
Highly Insulated Hydrogen Powered Vacuum Gasochromic Smart Windows for Energy-Efficient Buildings	2024	Journal of Building Engineering	[175]
Potential of emerging glazing technologies for highly glazed buildings in hot arid climates.	2008	Energy and Buildings	[176]

Title	Year	Journal/Conference	Ref.
Energy assessment of gasochromic smart windows for a high-rise apartment block in a temperate climate	2024	Journal of Building Engineering	[177]
Polymer-Dispersed Liquid Crystal (PDLC) smart switchable windows for less-energy hungry buildings and visual comfort in hot desert climate	2022	Journal of Building Engineering	[178]
Design optimization of smart glazing optical properties for office spaces	2022	Applied Energy	[179]
Multi-objective optimization of thermochromic glazing based on daylight and energy performance evaluation	2021	Building Simulation	[180]
Using smart glazing for reducing energy consumption on existing office building in hot dry climate	2020	HBRC Journal	[72]
Color rendering performance of smart glazings for building applications	2018	Solar Energy	[181]
Analysis of the energy and visual performance of a building with photochromic windows for a location in southern Italy	2022	Building and Environment	[50]
Energy and daylighting performance of building integrated spirooxazine photochromic films	2022	Solar Energy	[182]
Static and dynamic glazing integration for enhanced building efficiency and indoor comfort with thermochromic and electrochromic windows.	2024	Thermal Science and Engineering Progress	[151]
Cooperative performance of potentially developed thermochromic glazing under different climates	2019	Energy Procedia	[183]
Decision-making process for thermal comfort and energy efficiency optimization coupling smart-window and natural ventilation in the warm and hot climates	2022	Energy and Buildings	[184]
Optimal control parameter for electrochromic glazing operation in commercial buildings under different climatic conditions	2020	Applied Energy	[185]
Smart double glazing integrated polymer dispersed liquid crystal for enhancing building's thermal performance in hot-arid climate	2023	Journal of Building Engineering	[76]
Enhancing building thermal performance in Saudi's extreme climates through reversible smart insulated window glazing: Laboratory-scale experiments.	2023	Energy for Sustainable Development	[186]
Smart windows—Dynamic control of building energy performance	2017	Energy and Buildings	[187]
Effect of Smart Glazing Window on Energy Consumption Inside Office Building	2020	Materials Science Forum	[188]
Smart windows – Transmittance tuned thermochromic coatings for dynamic control of building performance	2021	Energy and Buildings	[189]
Energy Performance and Comfort Analysis of Three Glazing Materials with Distinct Thermochromic	2024	Buildings	[190]

Title	Year	Journal/Conference	Ref.
Responses as Roller Shade Alternative in Cooling- and Heating-Dominated Climates			
Evaluation of Building Energy and Daylight Performance of Electrochromic Glazing for Optimal Control in Three Different Climate Zones	2019	Sustainability	[191]
Development of a Comparison-based Control Strategy of Electrochromic Glazing for the Management of Indoor Lighting and Energy Efficiency	2019	Conference: 2018 Building Performance Analysis Conference and SimBuildAt: Chicago, IL	[192]
A comparative energy analysis of three electrochromic glazing technologies in commercial and residential buildings	2017	Applied Energy	[193]
Thermal and visual performance of real and theoretical thermochromic glazing solutions for office buildings	2016	Solar Energy Materials and Solar Cells	[194]

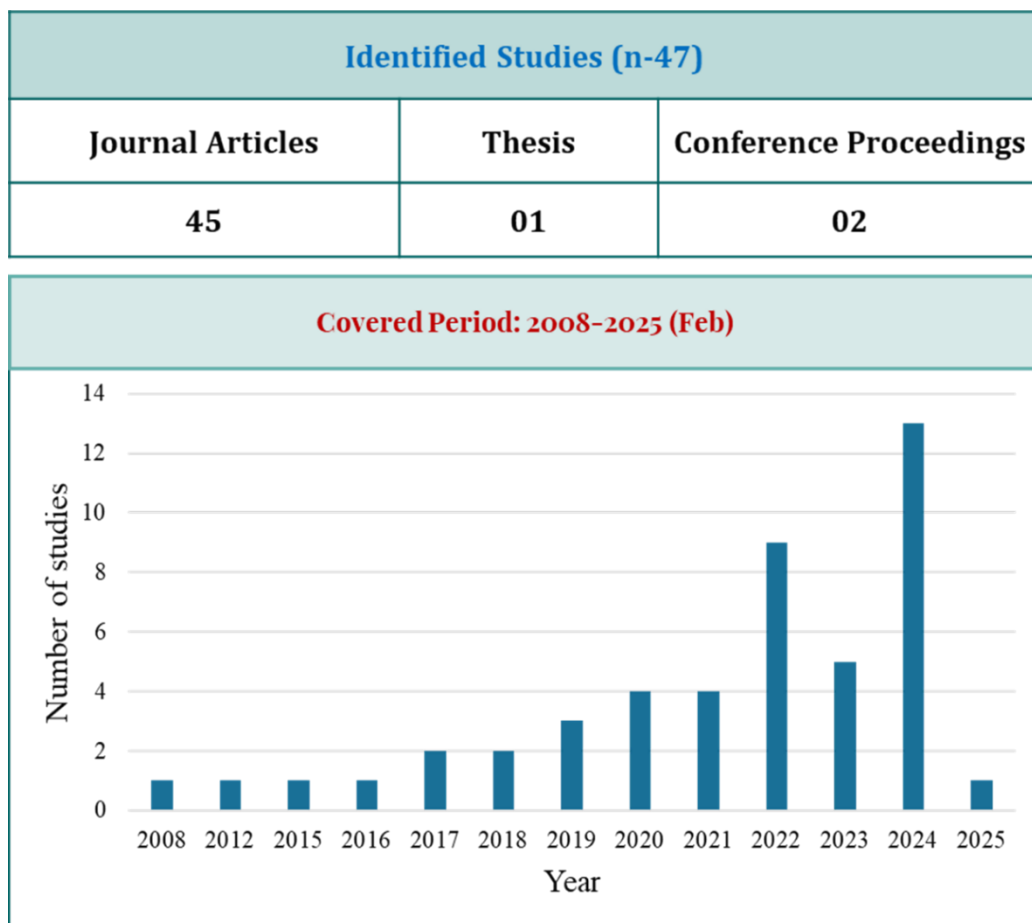


Figure 23: Overview of studies

4.1.2 Overview of Study Characteristics

This section provides a detailed overview of the study characteristics extracted from the 47 reviewed studies, emphasizing key aspects relevant to the sustainability assessment of smart glazing technologies. Comprehensive extracted data, including the smart glazing type, building type, geographical location, climate classification, and performance assessment metrics (main and sub-criteria), as comprehensively presented in *Appendix 1*. The systematic review identified a range of smart glazing technologies assessed across various studies. **Figure 24** illustrates the frequency of occurrence for different smart glazing alternatives. Electrochromic (EC) glazing emerged as the most frequently assessed technology, appearing in 24 studies. Thermochromic (TC) glazing was also significantly represented with 14 occurrences. Other glazing technologies, including Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Gasochromic (GC), Photochromic (PC), and Thermotropic (TT), were comparatively less prevalent. This diversity reflects the broad scope of smart glazing technologies currently explored in building applications.

The studies predominantly investigated non-domestic buildings, aligning with this thesis's research objectives. As illustrated in Figure 25, approximately 60% of the studies (28 studies) concentrated on office buildings, underlining a strong research emphasis on non-domestic buildings. Other building types explored included hotels and apartment towers, test cells, educational buildings, and sunroom.

The geographic distribution of studies, visually represented in Figure 26, highlights significant attention towards regions experiencing hot climatic conditions, particularly in the Middle East (Saudi Arabia, Egypt), Asia (India, China), North America (USA), and Mediterranean Europe (Italy, Greece, Portugal). Climatic conditions identified from these

regions predominantly included hot desert, arid, semi-arid, and humid subtropical climates, directly aligning with the climatic focus of this thesis.

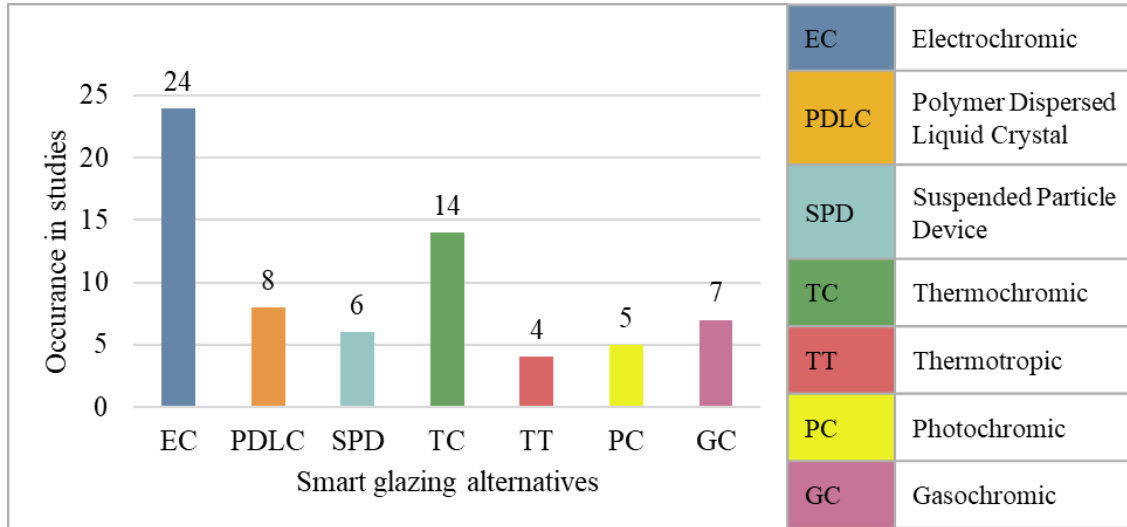


Figure 24: Frequency of occurrence of smart glazing

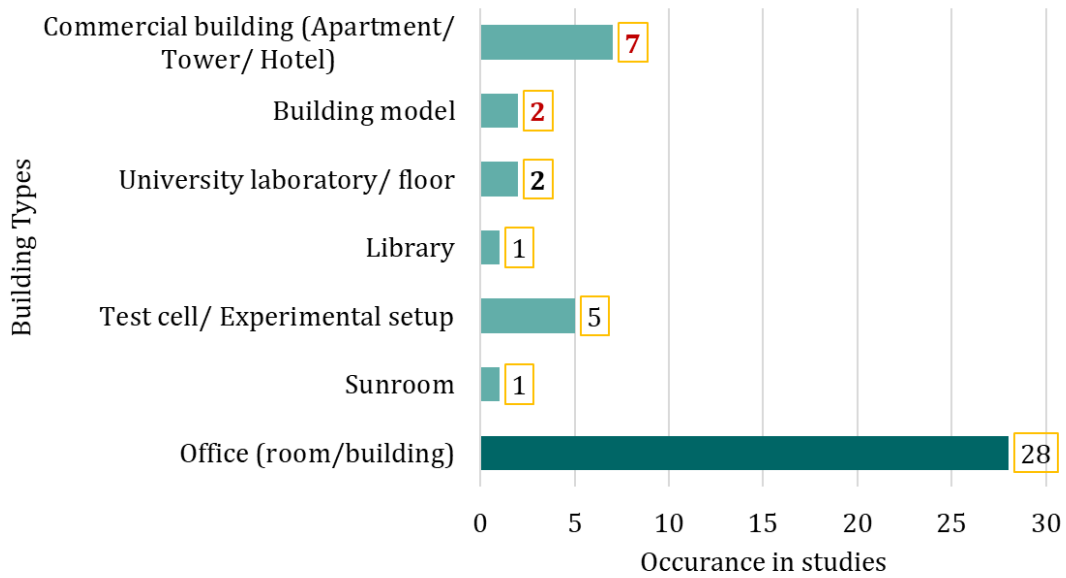


Figure 25: Distribution of building types in studies

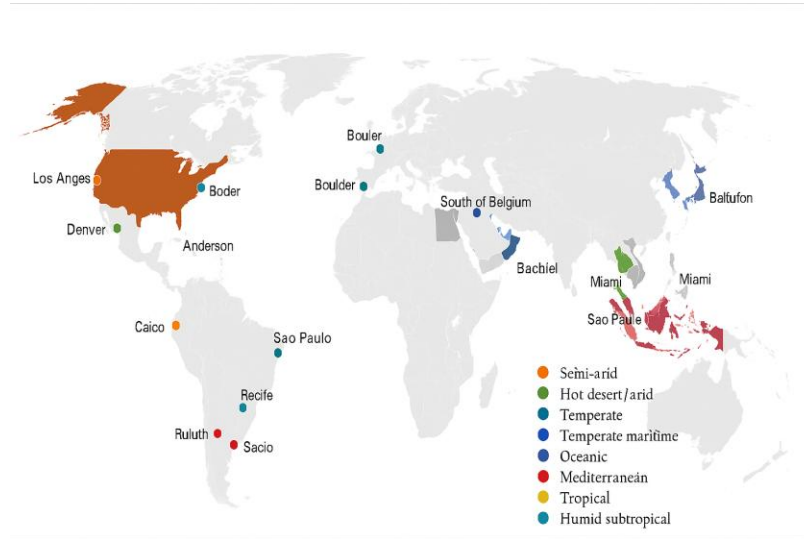


Figure 26: Geographical distribution of studies

An essential outcome of the systematic literature review was the identification of sustainability assessment criteria relevant to smart glazing technologies. A total of 108 distinct sub-criteria were extracted from the reviewed studies. The synthesized results, including frequency of occurrence across all main categories and sub-criteria, are detailed in *Appendix 2*. Among the main criteria, Opto-Thermal Properties appeared most frequently, followed by Visual Comfort and Daylighting, Energy, and Thermal Comfort.

4.2 Sustainability Criteria Analysis

4.2.1 Curated and Categorized Criteria

The initial set of criteria identified through the SLR was considerably broad. While a comprehensive list enhances the validity and robustness of the assessment decision framework, an excessively large number of criteria may introduce redundancy, reduce clarity, and hinder the practical application of the decision-making process [106]. Consequently, a systematic curation process was implemented to refine, filter, and organize the criteria based on relevance, clarity, and alignment with the study's objectives.

Notably, the original criteria were grouped under general performance themes such as thermo-optical properties, energy consumption, and thermal comfort without explicit association to the core sustainability dimensions. To address this limitation and improve the structural coherence of the framework, all identified criteria were carefully re-evaluated and reclassified. Following this refinement, both the main criteria and their associated sub-criteria were structured under four overarching sustainability dimensions (Figure 27):

- **Environmental**
- **Social (Occupant Comfort)**
- **Economic**
- **Technical**

The Environmental dimension included criteria related to energy efficiency, water consumption, and waste management, addressing the environmental impact of smart glazing technologies. The Social dimension encompassed criteria linked to visual comfort, daylighting, thermal comfort, and health and well-being, reflecting the user-centric and social benefits of glazing systems. The Economic dimension focused on cost-related aspects, including glazing cost and energy savings, while the technical dimension covered operational aspects, such as durability, switching time, and power requirements for glazing states.

This structured arrangement was essential to provide a clear and comprehensive framework for evaluating smart glazing technologies. Each sub-criterion was carefully assessed and assigned to a specific sustainability dimension and criterion based on its **relevance and alignment** with the study's objectives.

Some sub-criteria were relevant to more than one dimension, necessitating careful deliberation to determine their most appropriate categorization. For instance, Daylight

Autonomy (DA) could reasonably fall under both Environmental (for its contribution to energy efficiency) and Social (for its impact on occupant comfort) dimensions. In such cases, the sub-criterion was assigned to the dimension with which it aligned more strongly to maintain consistency and clarity in the framework. This decision-making process was supported by a brainstorming session, where overlaps were resolved, and the categorization of criteria and sub-criteria was critically evaluated.

Moreover, input from thesis supervisors played a significant role in refining the criteria and sub-criteria further. Some criteria not explicitly mentioned in the literature but considered important for the framework's robustness were added. For example, End-of-Life Disposal or Recycling was introduced under Environmental criteria to address lifecycle sustainability considerations, which were deemed crucial at the initial state for comprehensive assessment.

The final categorization process resulted in the organization of **9 main criteria and 47 sub-criteria** across four sustainability dimensions: Environmental, Social, Economic, and Technical. This structured categorization ensured that all aspects of sustainability were comprehensively represented, creating a balanced and cohesive hierarchy for assessing smart glazing technologies. The resulting categorized hierarchy provides a transparent and systematic structure that is the foundation for evaluating smart glazing technologies. Further validation of these criteria and sub-criteria was conducted through a structured survey detailed in the subsequent sections.

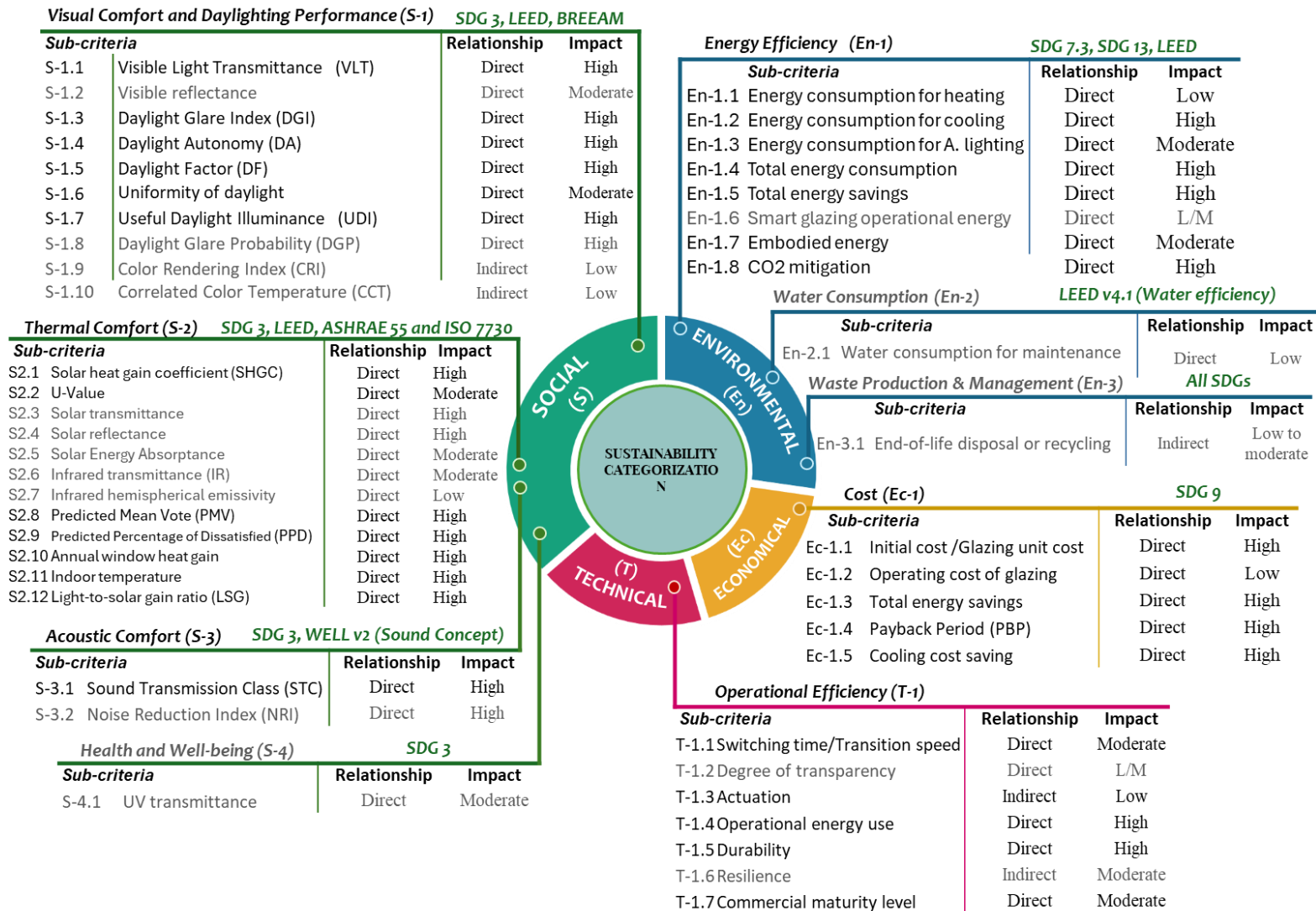


Figure 27: Curated and categorized sustainability criteria

The relevance of each main category and its corresponding sub-criteria, along with their alignment to sustainability, will be examined in the subsequent sections. This analysis aims to justify the inclusion and classification of each criterion within the four sustainability dimensions.

4.2.2 Relevance to Sustainability

The curated set of criteria was systematically classified into four core sustainability dimensions: Environmental, Social, Economic, and Technical, to ensure a structured and holistic sustainable evaluation of smart glazing systems. This classification aligns with internationally recognized sustainability frameworks, including the United Nations Sustainable Development Goals (SDGs), LEED, BREEAM, and ISO 21929-1 for sustainable construction.

a) Environmental Dimension

This dimension encompasses criteria that address the environmental performance of smart glazing systems, including energy consumptions, energy savings, and emissions. The main criteria categorized here are:

- **Energy Efficiency (En-1)**

Energy efficiency refers to the ability to achieve optimal performance using minimal energy inputs. It plays a crucial role in reducing operational energy consumption, particularly for cooling and lighting in hot climates. Enhancing energy efficiency helps lower greenhouse gas emissions, reduces reliance on non-renewable resources, and supports the overall decarbonization of buildings [195]. These environmental benefits make energy efficiency a core criterion under the Environmental sustainability dimension.

This criterion is strongly aligned with **SDG 7 (Affordable and Clean Energy)**, especially **SDG 7.3 (Energy Efficiency)**, which emphasizes improving energy efficiency globally [196]. It also supports **SDG 13 (Climate Action)** by contributing to building sector decarbonization through reduced CO₂ emissions [195]. Moreover, energy performance is a central component in global green building certifications such as LEED Energy and Atmosphere (EA) category [197, 198].

- **Water Consumption (En-2)**

Water usage has a significant impact on the environment, especially when it comes to greenhouse gas emissions and water scarcity [199]. Water use in building operations, especially for cleaning and maintenance of glazing, has environmental implications related to freshwater resource depletion and energy use associated with water treatment and distribution. In arid and semi-arid regions, water conservation becomes even more critical.

This criterion aligns with SDG 6 (Clean Water and Sanitation), promoting low-maintenance and water-efficient technologies [166]. Moreover, international frameworks like LEED v4.1 (Category: Water efficiency) also recognize the importance of water efficiency, award water efficiency points based on the water performance score [200].

- **Waste Production and Management (En-3)**

This criterion focuses on the waste generated during the life cycle of smart glazing, including manufacturing residues, packaging, and end-of-life disposal. Sustainable waste management promotes the reuse, recycling, and recovery of materials, thereby reducing the environmental burden of landfills and incineration [201].

Studies highlight that waste reduction efforts are cross-cutting and indirectly contribute to all 17 SDGs [202].

b) Social Dimension

The Social dimension addresses human-centric aspects of sustainability, particularly those related to occupant well-being, comfort, and health. In the context of smart glazing systems, the following main criteria were categorized under this dimension:

- **Visual Comfort and Daylighting Performance (S-1)**

This criterion addresses multiple parameters essential for achieving a visually comfortable indoor environment. These include sufficient daylight provision, uniform daylight distribution, the absence of glare, and a balanced integration of natural and artificial lighting. Such factors are known to improve occupant mood, focus, and productivity, and overall well-being [203, 204].

This criterion supports **SDG 3 (Good Health and Well-being)** [205]. It is also embedded in international certification systems such as LEED (Indoor Environmental Quality) and BREEAM (Visual Comfort), as illustrated in Table 21 [206, 207].

Table 21: LEED and BREEAM visual comfort and daylighting parameters

LEED	BREEM
• Interior lighting (2 credit points) • Daylight and quality views (4 credit points)	• Glare Control • Daylighting • View out • Internal and external lighting levels, zoning, and control

- **Thermal Comfort (S-2)**

Thermal comfort refers to the state of mind that expresses satisfaction with the surrounding thermal environment. It is a key determinant of occupant performance, comfort, and health [208].

This criterion aligns with **SDG 3 (Good Health and Well-being)** [205]. It is formally recognized in **LEED** (Indoor Environmental Quality), which includes credits for thermal comfort performance based on established standards such as **ASHRAE 55** and **ISO 7730** [206, 209].

- **Acoustic Comfort (S-3)**

Acoustic comfort involves minimizing unwanted noise levels and enhancing sound quality within indoor environments. It is especially important in settings like schools, offices, and healthcare facilities where concentration, communication, and overall comfort can be affected by noise. [210]

The promotion of healthy acoustic environments aligns with **SDG 3 (Good Health and Well-being)** [205] and is emphasized in building rating systems such as **WELL v2 (Sound Concept)** which encourage noise reduction strategies and sound insulation [211].

- **Health and Well-being (S-4)**

This criterion focuses on protecting occupants from environmental hazards such as ultraviolet (UV) radiation, ensuring healthy indoor environments beyond conventional comfort parameters. In terms of sustainability alignment, this criterion strongly supports **SDG 3 (Good Health and Well-being)** [205].

c) **Economical Dimension**

The Economic dimension evaluates the affordability, cost-effectiveness, and long-term financial implications of smart glazing systems. This includes initial capital investment, potential savings in energy costs, and payback period.

- **Cost (Ec-1)**

Cost is the primary criterion under this dimension, encapsulating all economic aspects of smart glazing implementation. Economic viability is a critical aspect for technology adoption, particularly in developing regions or for budget-sensitive projects. The inclusion of this criterion ensures that financial sustainability is considered alongside environmental and social performance.

This criterion supports **SDG 9** (Industry, Innovation, and Infrastructure) by promoting investment in sustainable building technologies [212].

d) Technical Dimension

The Technical dimension assesses the functional and technological performance of smart glazing systems, focusing on reliability, durability, responsiveness, and integration capability. This ensures that the systems perform effectively in real-world building operations and climatic conditions.

- **Operational Efficiency (T-1)**

Operational Efficiency (T-1) covers several aspects, including switching time, energy demand for modulation, durability over time, and the commercial maturity of the technology. These characteristics determine not only the ease of use and long-term performance of the glazing system but also its sustainability impact. For instance, a durable and resilient product reduces replacement frequency and associated waste, while commercially mature technologies offer greater reliability and easier integration.

Table 22: Summary sustainability relevance

Sustainability dimension	Main criteria	Aligned SDGs / Frameworks
Environmental	Energy Efficiency (En-1)	SDG 7.3 SDG 13 LEED (Category: Energy and Atmosphere)
	Water Consumption (En-2)	LEED v4.1 (Water efficiency)
	Waste Production and Management (En-3)	---
	Visual Comfort and Daylighting (S-1)	SDG 3 LEED (Indoor Environmental Quality) BREEAM (Visual Comfort)
Social	Thermal Comfort (S-2)	SDG 3 LEED (Indoor Environmental Quality) ASHRAE 55 and ISO 7730
	Acoustic Comfort (S-3)	SDG 3 WELL v2 (Sound Concept)
	Health and Well-being (S-4)	SDG 3
Economic	Cost (Ec-1)	SDG 9
Technical	Operational Efficiency (T-1)	---

4.2.3 Criteria Relationship and Impact Analysis

A sustainability indicator is a quantitative or qualitative attribute that signifies a desired outcome aimed at accomplishing sustainability objectives [213]. Generally, quantitative indicators are preferred over qualitative indicators since they are easier to manage and can be monitored statistically. Nonetheless, a comprehensive methodology must consider both sorts of indicators. [214]

This section analyzes how each sustainability sub-criterion influences the selection of smart glazing systems for non-domestic buildings, especially in hot climates. The analysis focuses on two attributes:

- **Relationship Type:** Whether the influence of the criterion on glazing selection is direct or indirect.

- **Impact Level:** The magnitude of this influence on decision-making (Low, Moderate, High).
- Note that this analysis was conducted with the assistance of **AI tools** to ensure a structured and consistent evaluation of each criterion. The most frequently occurring outputs were considered for the final assessment.

a) Environmental Sustainability

Environmental sustainability captures the impact of smart glazing systems on energy consumption, emissions, and lifecycle ecological effects. The three main criteria analyzed here are Energy Efficiency (En-1), Water Consumption (En-2), and Waste Management (En-3). Table 23 presents an overview of environmental sub-criteria and their influence on smart glazing selection.

- **Energy Efficiency (En-1)** includes sub-criteria such as energy consumption for cooling, lighting, and heating, total energy savings, operational energy of smart glazing, and embodied energy. These parameters directly affect the overall building energy performance. For instance, cooling energy consumption (En1.2), total energy consumption (En1.4), and CO₂ mitigation (En1.8) demonstrate a high impact, as smart glazing significantly reduces cooling loads in hot climates. Indicators such as operational energy (En1.6) or embodied energy (En1.7) have a moderate influence due to variability across glazing technologies.
- **Water Consumption (En-2)** evaluates the water required for maintenance during the operational phase. Its impact is relatively low but becomes more relevant in water-scarce regions, justifying its inclusion under this dimension.

- **Waste Production and Management (En-3)** considers recyclability and end-of-life strategies. Though the impact is indirect and moderate to low, lifecycle waste reduction aligns with broader sustainability goals.

Table 23: Environmental sub-criteria and their relationship to smart glazing selection

Main criteria	Sub-criteria	Relationship	Impact
		Direct/Indirect	Low/Moderate/High
Energy Efficiency (En-1)	Energy consumption for heating (En1.1)	Direct	Low
	Energy consumption for cooling (En1.2)	Direct	High
	Energy consumption for artificial lighting (En1.3)	Direct	Moderate
	Total energy consumption (HVAC, lighting) (En1.4)	Direct	High
	Total energy savings (En1.5)	Direct	High
	Smart glazing operational energy (En1.6)	Direct	Low to Moderate
	Embodied energy (En1.7)	Direct	Moderate
	CO2 mitigation (En1.8)	Direct	High
Water Consumption (En-2)	Water consumption for maintenance (En2.1)	Direct	Low
Waste Production and Management (En-3)	End-of-life disposal or recycling (En3.1)	Indirect	Low to moderate
Based on AI-assisted assessment			

b) Social Sustainability

The social sustainability dimension evaluates smart glazing systems based on their contribution to occupant comfort, well-being, and overall quality of life. This includes factors related to visual, thermal, and acoustic environments, as well as occupant health. Table 24 summarizes the relationship and impact of social sustainability indicators on smart glazing selection.

- **Visual Comfort and Daylighting (S-1)** is assessed through several parameters such as VLT, glare index, UDI, daylight autonomy, and daylight uniformity. These metrics

evaluate the ability of smart glazing to optimize natural lighting conditions while minimizing glare and ensuring visual comfort. Most sub-criteria under this category exhibit a direct relationship with smart glazing performance. For instance, VLT, daylight autonomy, and UDI have a high impact on the decision-making process due to their direct role in reducing artificial lighting needs and enhancing occupant satisfaction.

- **Thermal Comfort (S-2)** indicators include solar heat gain coefficient (SHGC), U-value, shading coefficient, solar and infrared transmittance, PMV, and PPD. These sub-criteria directly relate to how smart glazing manages solar radiation, internal heat gain, and indoor temperature control. Metrics such as SHGC, solar transmittance, and PMV are considered to have high influence in hot climatic zones due to their role in mitigating overheating and enhancing HVAC efficiency.
- **Acoustic Comfort (S-3)** is assessed using Sound Transmission Class (STC) and Noise Reduction Index. Both parameters measure the glazing's ability to insulate against external noise. Given the direct relevance of these metrics to noise control and overall occupant comfort, their impact is considered high.
- **Occupant Health (S-4)** focuses on the transmission of ultraviolet (UV) radiation through glazing. This sub-criterion has a direct impact on reducing occupants' exposure to harmful UV rays, promoting health and well-being. While its impact is rated as moderate compared to thermal and visual factors, it remains relevant in the selection process for ensuring occupant safety.

Table 24: Social sub-criteria and their relationship with smart glazing selection

Main criteria	Sub-criteria		Relationship	Impact
			Direct/Indirect	Low/Moderate/High
Visual Comfort and Daylighting (S-1)	S1.1	Visible light transmittance (VLT)	Direct	High
	S1.2	Visible reflectance	Direct	Moderate
	S1.3	Glare index / Daylight glare index (DGI)	Direct	High
	S1.4	Daylight autonomy (DA)	Direct	High
	S1.5	Daylight factor (DF)	Direct	High
	S1.6	Uniformity of daylight	Direct	Moderate
	S1.7	Useful daylight illuminance (UDI)	Direct	High
	S1.8	Daylight glare probability (DGP)	Direct	High
	S1.9	Color rendering index (CRI)	Indirect	Low
	S1.10	Correlated color temperature (CCT)	Indirect	Low
Thermal Comfort (S-2)	S2.1	Solar heat gain coefficient (SHGC)	Direct	High
	S2.2	U-Value	Direct	Moderate
	S2.3	Solar transmittance	Direct	High
	S2.4	Solar reflectance/ Solar energy reflectance	Direct	High
	S2.5	Solar Energy Absorptance	Direct	Moderate
	S2.6	Infrared transmittance (IR)	Direct	Moderate
	S2.7	Infrared hemispherical emissivity	Direct	Low
	S2.8	Predicted Mean Vote (PMV)	Direct	High
	S2.9	Predicted Percentage of Dissatisfied (PPD)	Direct	High
	S2.10	Annual window heat gain	Direct	High
	S2.11	Indoor temperature	Direct	High
	S2.12	Light-to-solar gain ratio (LSG)	Direct	High
Acoustic Comfort (S-3)	S3.1	Sound Transmission Class (STC)	Direct	High
	S3.2	Noise Reduction Index	Direct	High
Occupant Health (S-4)	S4.1	UV transmittance	Direct	Moderate
Based on AI-assisted assessment				

c) Economic Sustainability

Economic sustainability considers the financial feasibility of implementing smart glazing systems. The single main criterion under this dimension is Cost (Ec-1), which includes sub-criteria such as initial cost, operating cost, energy cost savings, and payback period. Table

25 summarizes the relationship and impact of social sustainability indicators on smart glazing selection.

Initial cost (Ec1.1) represents the upfront investment required for purchasing and installing the glazing. This has a high impact on decision-making as cost is often a key constraint in building projects. Operating cost (Ec1.2) evaluates the ongoing operational expenses of smart glazing, which are very low. Energy cost savings and payback period both have a high influence, especially in hot climates, as they directly quantify the economic benefits and financial return on investment.

Table 25: Economic sub-criteria and their relationship to smart glazing selection

	Sub-criteria		Relationship	Impact
			(Direct/Indirect)	(Low/Moderate/High)
Cost (Ec-1)	Ec1.1	Initial cost /Glazing unit cost	Direct	High
	Ec1.2	Operating cost of glazing	Direct	Low
	Ec1.3	Total Savings in air conditioning	Direct	High
	Ec1.4	Payback period (PBP)	Direct	High
	Ec1.5	Cooling cost saving	Direct	High
Based on AI-assisted assessment				

d) Technical Sustainability

The technical dimension evaluates the operational performance and technological readiness of smart glazing systems, which are essential for ensuring consistent and efficient performance over time. This includes criteria such as switching speed, energy requirements, durability, adaptability to environmental conditions, and market maturity. Table 26 summarizes these technical sub-criteria and their relevance.

Operational efficiency (T-1) encompasses several sub-criteria. Transition speed and energy requirements have a direct relationship with glazing performance as they affect system responsiveness and operational energy demand. Durability and resilience are considered to

have a high impact due to their role in determining the lifespan and environmental adaptability of glazing in harsh, hot climates. On the other hand, actuation and commercial maturity are classified as indirect, with moderate and low impacts, respectively, as they influence feasibility and adoption rather than core performance.

Table 26: Technical Sub-Criteria and Their Relationship with Smart Glazing Selection

	Sub-criteria		Relationship	Impact
			(Direct/Indirect)	(Low/Moderate/High)
Operational efficiency (T-1)	T1.1	Transition speed/ Switching time	Direct	Moderate
	T1.3	Power requirement for the glazing state	Direct	Low to moderate
	T1.4	Actuation	Indirect	Low
	T1.5	Durability	Direct	High
	T1.6	Resilience	Direct	High
	T1.7	Commercial maturity level	Indirect	Moderate
<i>Based on AI-assisted assessment</i>				

4.3 Questionnaire Results and Analysis

The primary objective of the questionnaire was to refine and validate the curated criteria and sub-criteria based on their perceived importance in selecting the most sustainable smart glazing option for non-domestic buildings in hot climatic regions. To ensure the relevance and applicability of the selected criteria, feedback was solicited from both industry and academic experts. This process aimed to eliminate less critical criteria and streamline the selection process, facilitating its practical application in real-world contexts. The responses provided critical insights into the significance, feasibility, and prioritization of the identified criteria and sub-criteria, forming the foundation for the final selection framework. This section presents an in-depth analysis of the empirical data collected through the questionnaire survey.

A total of 140 experts were contacted, with **100 approached through LinkedIn and 40 via email**. The research participation process included an initial invitation followed by two reminders and in some cases, up to three follow-ups. From this effort, 24 responses were received, out of which **22 completed questionnaires** were deemed valid and included in the final analysis, resulting in an overall response rate of **15.71%**.

4.3.1 Profile of Questionnaire Respondents

The respondents for this study were carefully selected based on their expertise and relevance to the research objectives. These individuals were chosen for their direct involvement in decision-making processes related to building material selection, smart and sustainable building technologies, and sustainability initiatives. The questionnaire included a section dedicated to collecting participant information such as name, title or position, organizational affiliation, areas of expertise, and years of professional experience to ensure a broad representation of perspectives.

The geographic distribution of respondents covered multiple regions, categorized and mentioned in **Figure 28**. The inclusion of experts from these regions enhances the study by incorporating insights from professionals working in varied environmental contexts, particularly hot climatic regions. The highest representation was from the Middle East, primarily from Saudi Arabia, followed by respondents from Europe and Asia.

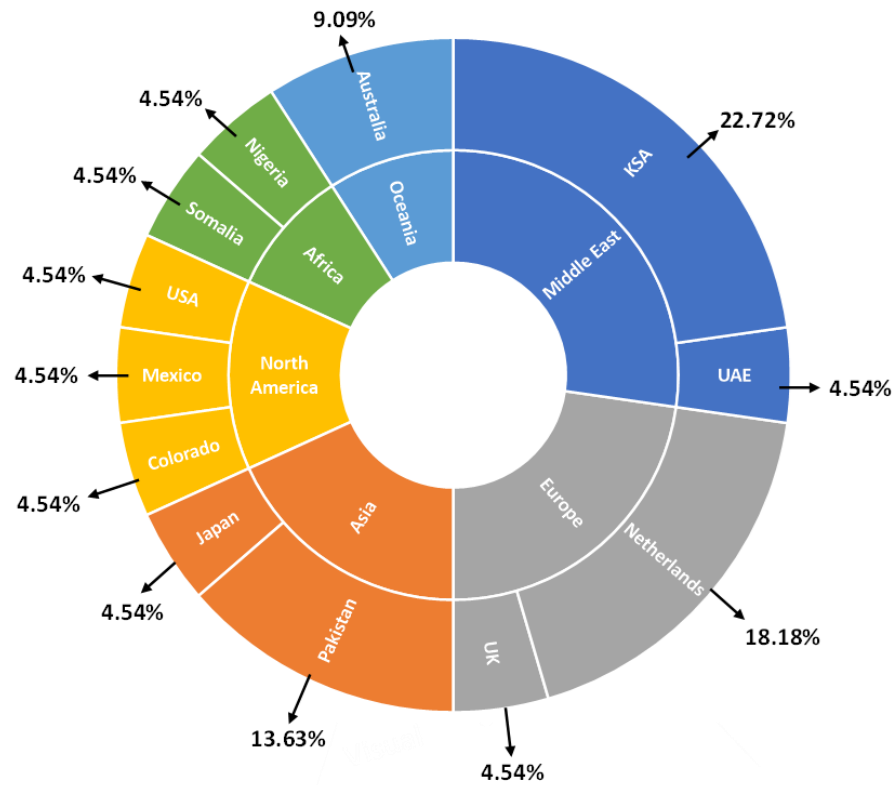


Figure 28: Geographic distribution of survey respondents

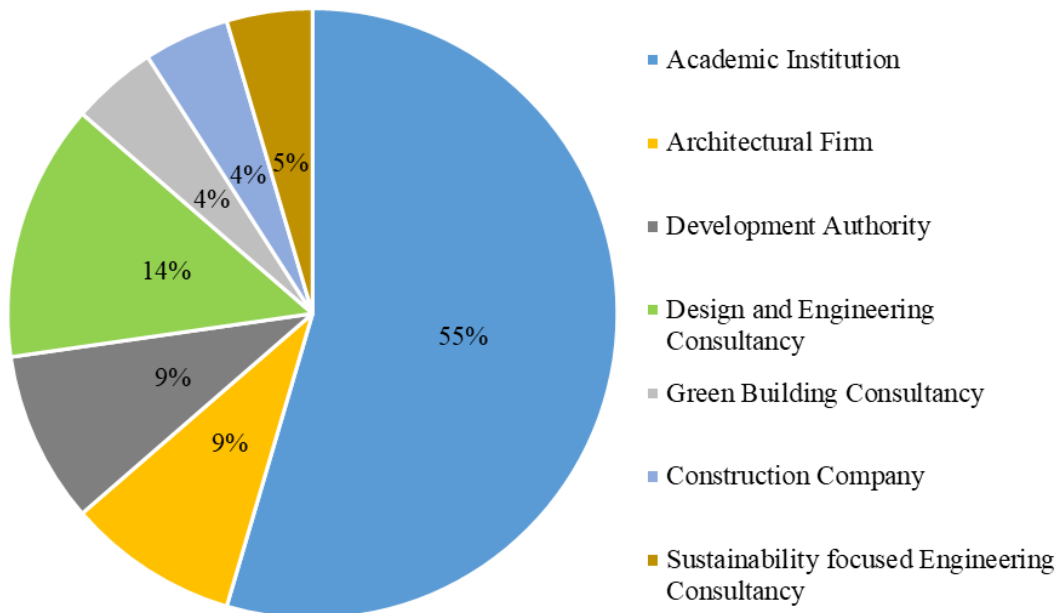


Figure 29: Distribution of respondents by organization type

The respondents represented a diverse set of organizations, with the majority affiliated with academic institutions (55%), while others belonged to architectural firms, engineering consultancies, green building consultancies, and governmental or development authorities, as shown in **Figure 29**. The inclusion of professionals from both academic and industrial sectors helped ensure a holistic understanding of sustainability in smart glazing technologies. Participants held various professional titles, including Professors, Associate Professors, CEOs, Managing Directors, PhD Candidates, Postdoctoral Researchers, Sustainability Consultants, and Building Performance Analysts. This broad representation underscores the relevance and credibility of the survey results.

The respondents' years of professional experience ranged from 4 to over 41 years, providing a broad spectrum of perspectives. The distribution of experience levels of respondents is summarised as follows:

- **Fewer than 5 years:** 4.35% (1 respondent)
- **Between 5 and 15 years:** 52.17% (12 respondents)
- **Between 16 and 30 years:** 34.78% (8 respondents)
- **Over 30 years:** 8.70% (2 respondents)

The respondents' expertise spanned a diverse range of fields directly relevant to this study. The primary areas of expertise included building envelope performance, facade engineering, sustainable architecture, thermal and energy analysis, high-performance buildings, and green and sustainable buildings. Additionally, respondents demonstrated specialized knowledge in life cycle assessment (LCA), building information modeling (BIM), energy efficiency, material science and reuse, computational and urban design, and smart facade technologies. These areas of expertise were explicitly mentioned by the experts in the survey as their key knowledge domains related to smart glazing.

The diversity of respondents in terms of professions, organizational affiliations, years of professional experience, and areas of expertise enhances the credibility of this study. By integrating perspectives from academia, research, and industry, the findings reflect a broad spectrum of knowledge and expertise in the field of smart glazing technologies. *Table 69 (Appendix 4)* provides a detailed summary of the respondents, with each respondent assigned a unique identification number (ID 1-22) for reference.

4.3.2 Adequacy of Sample Size

The number of responses received in this survey (22 valid responses out of 140 invitations, a 15.71% response rate) is considered both adequate and sufficient for the given nature and scope of the study, followed by the specialized expertise of the respondents. While larger samples are often desirable for generalizability, the focus here is on **depth of insight** rather than statistical representativeness, as the study targets a niche domain (sustainable smart glazing for non-domestic buildings in hot climates).

4.3.3 Ranking Data Analysis of Questionnaire Responses/ Ranking Analysis

This section presents an analysis of the rating data collected using a five-point Likert scale, structured as follows: 1 = Not Important, 2 = Less Important, 3 = Moderate, 4 = Important, and 5 = Very Important. Each criterion and sub-criterion within the four key sustainability dimensions: Environmental, Social, Economic, and Technical was assessed using the Relative Importance Index (RII), mean values, standard deviation (SD), and coefficient of variation (CV). The analysis provides insights into expert agreement levels, where higher RII and mean values indicate that participants perceived the criterion or sub-criterion as highly important. The RII and mean values were calculated to rank the significance of each

factor, with lower-ranked criteria removed to maintain a streamlined and practical assessment framework.

The ranking analysis incorporated additional statistical metrics, including SD and CV, to indicate the level of agreement or variation in responses. Higher CV values suggest greater inconsistency among responses, whereas lower CV values reflect stronger consensus. A lower SD, typically close to or below 1.0, suggests strong agreement, while a higher SD signifies wider variations in expert opinions. To ensure the robustness of the sustainability assessment framework, criteria and sub-criteria that did not meet predefined thresholds were excluded to maintain reliability and practical applicability. For inclusion in the final sustainability assessment framework, the following conditions had to be met:

- **RII ≥ 0.60** , corresponding to a "High" importance ranking.
- **Mean value > 3.5** , ensuring the criterion was deemed sufficiently important.
- **CV $\leq 30\%$** , corresponding to "Moderate variability" thereby indicating a reasonable level of agreement among respondents.

Indicators that failed to meet these thresholds were considered for elimination.

Further analysis begins with an assessment of the main sustainability criteria, followed by an analysis of the sub-criteria within each dimension in the subsequent sections. The final assessment hierarchy prioritizes relevant and widely agreed-upon criteria and sub-criteria, ensuring scientific rigor and practical applicability. *Table 27* summarizes the rating responses of 22 participants for all criteria and sub-criteria.

Table 27: Rating responses of 22 respondents for criteria and sub-criteria

Main criteria/ Sub-criteria		Total responses	Not Important= 1	Less Important = 2	Moderate = 3	Very Important = 4	Extremely Important = 5
			%	%	%	%	%
En-1	Energy Efficiency	22	0.00	0.00	0.00	13.64	86.36
En-2	Water Consumption	22	27.27	27.27	22.73	18.18	4.55
En-3	Waste Production and Management	22	9.09	40.91	27.27	18.18	4.55
S-1	Visual Comfort and Daylighting Performance	22	0.00	0.00	4.55	36.36	59.09
S-2	Thermal Comfort	22	0.00	4.55	0.00	22.73	72.73
S-3	Acoustic Comfort	22	4.55	13.64	27.27	31.82	22.73
S-4	Health and Well-being	22	0.00	22.73	18.18	36.36	22.73
Ec-1	Cost	22	0.00	0.00	22.73	36.36	40.91
T-1	Operational Efficiency	22	0.00	4.55	18.18	45.45	31.82
En-1.1	Energy consumption for heating	22	0.00	4.55	22.73	36.36	36.36
En-1.2	Energy consumption for cooling	22	0.00	0.00	0.00	18.18	81.82
En-1.3	Energy consumption for artificial lighting	22	0.00	4.55	22.73	27.27	45.45
En-1.4	Total energy consumption	22	0.00	0.00	4.55	36.36	59.09
En-1.5	Total energy savings	22	0.00	0.00	0.00	31.82	68.18
En-1.6	Smart glazing operational energy	22	9.09	27.27	27.27	31.82	4.55
En-1.7	Embodied energy	22	4.55	22.73	27.27	36.36	9.09
En-1.8	CO2 mitigation	22	0.00	4.55	18.18	45.45	31.82
En-2.1	Water consumption for maintenance	22	18.18	36.36	27.27	9.09	9.09
En-3.1	End-of-life disposal or recycling	22	0.00	45.45	22.73	18.18	13.64
S-1.1	Visible Light Transmittance (VLT)	22	0.00	4.55	9.09	40.91	45.45
S-1.2	Visible reflectance	22	9.09	31.82	27.27	27.27	4.55
S-1.3	Daylight glare index (DGI)	22	0.00	9.09	13.64	18.18	59.09
S-1.4	Daylight Autonomy (DA)	22	0.00	0.00	13.64	27.27	59.09
S-1.5	Daylight Factor (DF)	22	0.00	4.55	9.09	45.45	40.91
S-1.6	Uniformity of daylight	22	0.00	9.09	22.73	36.36	31.82
S-1.7	Useful Daylight Illuminance (UDI)	22	0.00	4.55	9.09	40.91	45.45
S-1.8	Daylight Glare Probability (DGP)	22	4.55	4.55	22.73	22.73	45.45
S-1.9	Color Rendering Index (CRI)	22	0.00	45.45	18.18	27.27	9.09
S-1.10	Correlated Color Temperature (CCT)	22	0.00	45.45	13.64	22.73	18.18
S-2.1	Solar Heat Gain Coefficient (SHGC)	22	0.00	4.55	4.55	27.27	63.64
S-2.2	U-Value	22	0.00	4.55	9.09	27.27	59.09
S-2.3	Solar transmittance	22	9.09	4.55	4.55	50.00	31.82
S-2.4	Solar reflectance	22	9.09	22.73	18.18	36.36	13.64
S-2.5	Solar energy absorption	22	13.64	22.73	27.27	13.64	22.73
S-2.6	Infrared transmittance (IR)	22	9.09	18.18	45.45	18.18	9.09
S-2.7	Infrared hemispherical emissivity	22	9.09	36.36	22.73	27.27	4.55
S-2.8	Predicted Mean Vote (PMV)	22	4.55	4.55	22.73	50.00	18.18
S-2.9	Predicted Percentage of Dissatisfied (PPD)	22	4.55	9.09	13.64	54.55	18.18
S-2.10	Annual window heat gain	22	4.55	4.55	13.64	40.91	36.36
S-2.11	Indoor temperature	22	0.00	0.00	9.09	54.55	36.36
S-2.12	Light-to-solar gain ratio (LSG)	22	0.00	4.55	18.18	36.36	40.91
S-3.1	Sound Transmission Class (STC)	22	0.00	9.09	36.36	36.36	18.18
S-3.2	Noise Reduction Index (NRI)	22	0.00	9.09	31.82	40.91	18.18
S-4.1	UV transmittance	22	9.09	9.09	36.36	36.36	9.09
Ec-1.1	Initial cost /Glazing unit cost	22	4.76	0.00	4.76	19.05	71.43
Ec-1.2	Operating cost of glazing	22	19.05	19.05	14.29	38.10	9.52
Ec-1.3	Total energy savings	22	0.00	0.00	4.76	38.10	57.14
Ec-1.4	Payback Period (PBP)	22	4.76	4.76	28.57	23.81	38.10
Ec-1.5	Cooling cost saving	22	4.76	0.00	9.52	28.57	57.14
T-1.1	Switching time/Transition speed	22	0.00	4.55	18.18	27.27	50.00
T-1.2	Degree of transparency	22	4.55	13.64	27.27	31.82	22.73
T-1.3	Actuation	22	0.00	0.00	54.55	36.36	9.09
T-1.4	Energy /Power requirement for glazing state	22	13.64	4.55	59.09	18.18	4.55
T-1.5	Durability	22	0.00	0.00	13.64	18.18	68.18
T-1.6	Resilience	22	4.55	13.64	31.82	18.18	31.82
T-1.7	Commercial maturity level	22	0.00	0.00	27.27	27.27	45.45

4.3.3.1 Main Sustainability Criteria

As previously discussed, nine main criteria were identified across four key sustainability dimensions as follows:

- **Environmental:** Energy Efficiency (E-1), Water Consumption (E-2), Waste Production and Management (E-3)
- **Social:** Visual Comfort and Daylighting Performance (S-1), Thermal Comfort (S-2), Acoustic Comfort (S-3), Health and Well-being (S-4)
- **Economic:** Cost (E-1)
- **Technical:** Operational Efficiency (T-1)

All these criteria were analysed for importance levels and rankings, as Table 28 presents the comprehensive results of the main sustainability criteria, detailing the RII values, mean values, respective rankings, CV, and SD. Based on the ranking results, five main criteria received a **"Very High"** importance rating due to their high RII values as:

1. Energy Efficiency (RII = 0.973, Rank 1, CV = 7.22%)
2. Thermal Comfort (RII = 0.927, Rank 2, CV = 15.67%)
3. Visual Comfort and Daylighting Performance (RII = 0.909, Rank 3, CV = 13.11%)
4. Cost (RII = 0.836, Rank 4, CV = 19.01%)
5. Operational Efficiency (RII = 0.809, Rank 5, CV = 20.86%)

Moreover, these criteria also demonstrated mean value higher than 4, thereby demonstrating both high importance and a relatively low level of variability in expert responses, making them essential components of the final sustainability assessment framework.

Conversely, Water Consumption (RII = 0.491, CV = 49.86%) and Waste Production and Management (RII = 0.536, CV = 38.83%) received a **"Moderate"** importance rating, with mean values of **2.45 and 2.68, respectively**. Given that both criteria fail to meet the

predefined inclusion conditions, having an RII below 0.60 and mean values below 3.5, hence, they will be excluded from the final sustainability assessment framework. Additionally, their high CV values indicate significant variability in expert opinions, further justifying their removal due to inconsistency in perceived importance.

Among the social criteria, **Acoustic Comfort (0.709, CV = 32.25%)** and **Health and Well-being (0.718, CV = 30.58%)** present a borderline case, as their CV values are slightly above the threshold of 30%. However, their RII values exceed 0.60, and their mean values are slightly above 3.5, suggesting that they are still relevant for inclusion at this stage and analysis of their sub-criteria ranking might help in the decision.

In summary, Energy Efficiency, Thermal Comfort, Visual Comfort and Daylighting Performance, Cost, and Operational Efficiency are the top-ranked criteria and will be retained in the final framework. Meanwhile, Water Consumption and Waste Production and Management will be eliminated due to their low RII, low mean values, and high variability in expert opinions. This structured selection process ensures that the final assessment framework prioritizes the most critical factors for selecting sustainable smart glazing solutions in non-domestic buildings within hot climatic regions.

Table 28: Summary of main sustainability criteria rankings analysis

Sustainability dimensions	Main Criteria		RII	Importance Level	RII ranking	Mean value	SD	CV (%)
Environmental (En)	En-1	Energy Efficiency	0.97	Very High	1	4.86	0.35	7.2
	En-2	Water Consumption	0.49	Moderate	9	2.45	1.22	49.8
	En-3	Waste Production & Management	0.53	Moderate	8	2.68	1.04	38.8
Social (S)	S-1	Visual Comfort & Daylighting Performance	0.90	Very High	3	4.55	0.60	13.1
	S-2	Thermal Comfort	0.92	Very High	2	4.64	0.73	15.6
	S-3	Acoustic Comfort	0.70	High	7	3.55	1.14	32.2
	S-4	Health and Well-being	0.71	High	6	3.59	1.10	30.5
Economic (Ec)	Ec-1	Cost	0.83	Very High	4	4.18	0.80	19.0
Technical (T)	T-1	Operational Efficiency	0.80	Very High	5	4.05	0.84	20.8

4.3.3.2 Environmental Sub-criteria

Table 29 presents the ranking analysis of the sub-criteria under the Environmental dimension, which consists of three main criteria: Energy Efficiency (En-1), Water Consumption (En-2), and Waste Production and Management (En-3). The assessment includes **RII, mean value, SD, and CV** to evaluate expert consensus on the importance of each sub-criterion. As per the predefined thresholds (**$RII \geq 0.60$, mean value > 3.5 , $CV \leq 30\%$**), only the most important and relevant sub-criteria with strong consensus are considered for inclusion in the final sustainability assessment hierarchy. Additionally, the table shows two types of rankings: one reflecting each sub-criterion's position within the Environmental dimension ("**RII Ranking**") and one indicating its position across all sub-criteria of sustainability ("**Overall ranking**").

Within the Energy Efficiency category (En-1), **electricity consumption for cooling (En-1.2)** emerged as the highest-ranked sub-criterion, securing the first position within the Environmental dimension and overall ranking across all sub-criteria with an RII of 0.964 and a mean value of 4.82. The low CV of 8.19% indicates strong expert consensus on its importance, emphasizing the critical role of cooling-related electricity consumption in evaluating smart glazing systems, particularly for non-domestic buildings in hot climatic regions.

Following closely, **total energy savings (En-1.5)** was ranked second within the Environmental dimension and second overall, with an RII of 0.936 and a mean value of 4.68. This high rating underscores the importance of overall energy savings as a key performance indicator for sustainability. The CV of 10.18% further highlights the strong agreement among experts, reinforcing its significance. Additionally, **total energy consumption (AC, lighting) (En-1.4)** achieved the third position within the

Environmental dimension and third overall, with an RII of 0.909 and a mean value of 4.55. The CV of 13.11% indicates that experts largely agree on its importance, making it another essential factor in sustainability assessments.

Other energy-related sub-criteria also demonstrated strong relevance. **Electricity consumption for artificial lighting (En-1.3)** was ranked fourth in the Environmental dimension and seventeenth overall, with an RII of 0.827 and mean of 4.14. **Electricity consumption for heating (En-1.1)** and CO4 mitigation (En-1.8) both recorded an RII of 0.809 and a mean value of 4.05, ranking fifth within the Environmental dimension and twentieth overall. While their CV values (22.21% for heating and 20.86% for CO4 mitigation) indicate moderate variability, they remain within the acceptable range and thus qualify for inclusion in the final framework.

Conversely, several sub-criteria failed to meet the predefined inclusion thresholds. **Smart glazing operational energy (En-1.6)** recorded an RII of 0.591, a mean of 2.95, and CV of 36.90%, ranking ninth within the Environmental dimension and forty-second overall. The high variability in expert responses and the low mean value suggest a lack of agreement on its relevance, leading to its exclusion from the final framework. Similarly, **embodied energy (En-1.7)**, despite achieving an RII of 0.645, failed to meet the mean value requirement (3.23) and showed high variability (CV = 33.03%), ranking seventh within the Environmental category and thirty-fifth overall. Given these findings, it does not qualify for inclusion.

Beyond energy considerations, the Water Consumption (En-2) and Waste Production and Management (En-3) sub-criteria failed to achieve the required ranking for inclusion. **Water consumption for maintenance (En-2.1)** ranked tenth within the Environmental dimension and forty-seventh overall, with an RII of 0.509, a mean of 2.55, and CV of 46.53%. The

high variability and low mean value indicate a lack of agreement on its importance, making it unsuitable for the final framework. Similarly, **end-of-life disposal or recycling (En-3.1)** met the minimum RII threshold (0.600) but did not meet the required mean value (3.00) and demonstrated high variability (CV = 37.09%), ranking eighth within the Environmental dimension and thirty-ninth overall. As these were the only sub-criteria under their respective main criteria (En-2 and En-3), their exclusion led to the removal of the entire Water Consumption and Waste Production and Management categories. Furthermore, both En-2 and En-3 were already of "moderate" importance, reinforcing their limited relevance in the final sustainability assessment framework.

In summary, six sub-criteria under the Environmental dimension e.g., electricity consumption for cooling (En-1.2), total energy savings (En-1.5), total energy consumption (En-1.4), electricity consumption for heating (En-1.1), electricity consumption for artificial lighting (En-1.3), and CO₄ mitigation (En-1.8), are retained in the final sustainability assessment framework due to their high importance and strong expert consensus. The remaining sub-criteria e.g., smart glazing operational energy (En-1.6), embodied energy (En-1.7), water consumption for maintenance (En-2.1), and end-of-life disposal or recycling (En-3.1), are excluded due to lower relevance, high variability in expert responses, or both.

Table 29: Summary of sub-criteria rankings analysis under the environmental dimension

Main Criteria	Sub-criteria		RII	Importance Level	RII ranking	Overall ranking	Mean value	SD	CV (%)
Energy Efficiency (En-1)	En-1.1	Electricity consumption for heating	0.80	Very High	5	20	4.05	0.90	22.2
	En-1.2	Electricity consumption for cooling	0.96	Very High	1	1	4.82	0.39	8.1
	En-1.3	Electricity consumption for A. lighting	0.82	Very High	4	17	4.14	0.94	22.7
	En-1.4	Total energy consumption	0.90	Very High	3	3	4.55	0.60	13.1
	En-1.5	Total energy savings	0.93	Very High	2	2	4.68	0.48	10.1
	En-1.6	Smart glazing operational energy	0.59	Moderate	9	42	2.95	1.09	36.0
	En-1.7	Embodied energy	0.64	High	7	35	3.23	1.07	33.0

Main Criteria	Sub-criteria		RII	Importance Level	RII ranking	Overall ranking	Mean value	SD	CV (%)
	En-1.8	CO4 mitigation	0.80	Very High	5	20	4.05	0.84	20.8
Water Consumption (En-2)	En-2.1	Water consumption for maintenance	0.50	Moderate	10	47	2.55	1.18	46.5
Waste Production & Management (En-3)	En-3.1	End-of-life disposal or recycling	0.60	Moderate	8	39	3.00	1.11	37.0

4.3.3.3 Social Sub-Criteria

Table 30 presents the ranking analysis of the Social sub-criteria, covering four main categories: Visual Comfort and Daylighting Performance (S-1), Thermal Comfort (S-2), Acoustic Comfort (S-3), and Health and Well-being (S-4). Each sub-criterion was assessed based on RII, mean value, SD, and CV to determine its significance and expert consensus, following the predefined thresholds; only the most important and relevant sub-criteria are included in the final sustainability assessment hierarchy.

Among the sub-criteria under Visual Comfort and Daylighting Performance (S-1), **Daylight Autonomy (DA) (S-1.4)** achieved the highest ranking within this category and secured the sixth position overall, with an RII of 0.891 and a mean value of 4.45. Its low CV of 16.58% indicates strong agreement among experts on its significance in daylighting performance. Other key sub-criteria in this category include **Visible Light Transmittance (VLT) (S-1.1)**, **Daylight Glare Index (DGI) (S-1.3)**, and **Useful Daylight Illuminance (UDI) (S-1.7)**, each with an RII of 0.855 and a mean of 4.27, ranking second within the social dimension and tenth overall with CV less than 30%. These sub-criteria emphasize the importance of optimizing daylighting to enhance occupant comfort and reduce glare. Additionally, **Daylight Factor (S-1.5)** (RII = 0.845, mean = 4.23, CV = 19.2%) ranked third within this category and fourteenth overall, highlighting its significance in evaluating

daylight distribution inside buildings. Conversely, **Visible Reflectance (S-1.2)** (RII = 0.573, mean = 2.86, CV = 37.79%), **Color Rendering Index (CRI) (S-1.9)** (RII = 0.600, mean = 3.00, CV = 35.63%), and **Correlated Color Temperature (CCT) (S-1.10)** (RII = 0.627, mean = 3.14, CV = 38.48%) failed to meet the inclusion thresholds. Their high variability and lower perceived importance led to their exclusion from the final hierarchy.

Under the Thermal Comfort (S-2) criteria, **Solar Heat Gain Coefficient (SHGC) (S-2.1)** was the highest-ranked sub-criterion, securing fifth position overall, with an RII of 0.900 and a mean of 4.50. The low CV of 17.82% indicates a strong consensus on its importance in regulating solar heat gain through glazing. Similarly, **U-Value (S-2.2)** (RII = 0.882, mean = 4.41, CV = 19.37%) ranked seventh overall, underscoring its critical role in determining thermal insulation performance. **Light-to-Solar Gain Ratio (LSG) (S-2.12)** (RII = 0.827, mean = 4.14), ranking seventeenth overall, demonstrating its importance in balancing daylight access with heat gain. **Annual Window Heat Gain (S-2.10)** (RII = 0.800, mean = 4.00, CV = 26.73%) also ranked highly at twenty-second overall, highlighting its relevance in thermal comfort assessments. Conversely, sub-criteria such as **Infrared Hemispherical Emissivity (S-2.7)** (RII = 0.564, mean = 2.82, CV = 38.93%), **Infrared Transmittance (S-2.6)** (RII = 0.600, mean = 3.00, CV = 35.63%), and **Solar Energy Absorption (S-2.5)** (RII = 0.618, mean = 3.09, CV = 44.55%) exhibited low mean values and high variability, leading to their exclusion from the final framework.

Within the Acoustic Comfort (S-3) criteria, **Noise Reduction Index (S-3.2)** (RII = 0.736, mean = 3.68, CV = 24.27%) and **Sound Transmission Class (STC) (S-3.1)** (RII = 0.727, mean = 3.64, CV = 24.81%) ranked twenty-eighth and thirtieth overall, respectively. Both sub-criteria achieved the RII threshold of **0.60**, with mean values above 3.5, and moderate CV values indicate its inclusion in the framework.

For Health and Well-being (S-4), **UV Transmittance (S-4.1)** ranked thirty-fourth overall, with an RII of 0.655, a mean of 3.27, and a CV of 32.91%. While it meets the minimum RII requirement, its low mean value and high variability suggest a lack of strong agreement on its importance, leading to its exclusion from the final framework followed by the exclusion of its main criteria also e.g., **Health** and Well-being (S-4).

In summary, twelve sub-criteria under the social dimension met the predefined thresholds and are retained in the final framework. The remaining sub-criteria, Visible Reflectance (S-1.2), Color Rendering Index (CRI) (S-1.9), Correlated Color Temperature (CCT) (S-1.10), Infrared Hemispherical Emissivity (S-2.7), Infrared Transmittance (IR) (S-2.6), Solar Energy Absorption (S-2.5), and UV Transmittance (S-4.1) were excluded due to low importance, high variability in expert opinions, or both.

Table 30: Summary of sub-criteria rankings analysis under the social dimension

Main Criteria	Sub-criteria		RII	Importance Level	RII ranking	Overall ranking	Mean value	SD	CV (%)
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light transmittance (VLT)	0.855	Very High	4	10	4.27	0.83	19.36
	S-1.2	Visible reflectance	0.573	Moderate	24	44	2.86	1.08	37.79
	S-1.3	Glare index / Daylight glare index (DGI)	0.855	Very High	4	10	4.27	1.03	24.15
	S-1.4	Daylight autonomy (DA)	0.891	Very High	2	6	4.45	0.74	16.58
	S-1.5	Daylight factor	0.845	Very High	8	14	4.23	0.81	19.22
	S-1.6	Uniformity of daylight illuminance	0.782	High	12	24	3.91	0.97	24.85
	S-1.7	Useful daylight illuminance (UDI)	0.855	Very High	4	10	4.27	0.83	19.36
	S-1.8	Daylight glare probability (DGP)	0.800	High	10	22	4.00	1.15	28.87
	S-1.9	Color rendering index (CRI)	0.600	Moderate	22	39	3.00	1.07	35.63
	S-1.10	Correlated color temperature (CCT)	0.627	High	20	37	3.14	1.21	38.48
Thermal Comfort (S-2)	S-2.1	Solar heat gain coefficient (SHGC)	0.900	Very High	1	5	4.50	0.80	17.82
	S-2.2	U-Value	0.882	Very High	3	7	4.41	0.85	19.37
	S-2.3	Solar transmittance	0.782	High	12	24	3.91	1.19	30.48
	S-2.4	Solar reflectance	0.645	High	19	35	3.23	1.23	38.17
	S-2.5	Solar energy absorption	0.61	High	21	38	3.09	1.3	44.5
	S-2.6	Infrared transmittance (IR)	0.60	Moderate	22	39	3.00	1.7	35.6
	S-2.7	Infrared hemispherical emissivity	0.56	Moderate	25	46	2.82	1.1	38.9
	S-2.8	Predicted Mean Vote (PMV)	0.74	High	14	26	3.73	0.9	26.4
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	0.74	High	14	26	3.73	1.0	27.6

Main Criteria	Sub-criteria		RII	Importance Level	RII ranking	Overall ranking	Mean value	SD	CV (%)
	S-2.10	Annual window heat gain	0.80	High	10	22	4.00	1.0	26.7
	S-2.11	Indoor temperature	0.85	Very High	4	10	4.27	0.6	14.7
	S-2.12	Light-to-solar gain ratio (LSG)	0.82	Very High	9	17	4.14	0.8	21.4
Acoustic Comfort (S-3)	S-3.1	Sound Transmission Class (STC)	0.72	High	17	30	3.64	0.9	24.8
	S-3.2	Noise Reduction Index	0.73	High	16	28	3.68	0.8	24.2
Health and Well-being (S-4)	S-4.1	UV transmittance	0.65	High	18	34	3.27	1.0	32.9

4.3.3.4 Economical Sub-Criteria

Table 31 presents the ranking analysis of the Economic sub-criteria, focusing on Cost (Ec-1) as the main criterion. The evaluation considered RII, mean value, SD, and CV to assess expert consensus. Among the Economic sub-criteria, **Initial Cost/Glazing Unit Cost (Ec-1.1)** and **Savings in Air Conditioning (Ec-1.3)** ranked highest within this dimension, both achieving an RII of 0.864 and a mean value of 4.52, securing the eighth position overall. The low CV of 13.30% for **Ec-1.3** indicates strong agreement among experts regarding its importance in reducing operational costs. Following these, **Cooling Cost Saving (Ec-1.5)** (RII = 0.827, mean = 4.33, CV = 23.46%) ranked third within this category and seventeenth overall, emphasizing the role of glazing in energy savings. **Payback Period (Ec-1.4)** (RII = 0.736, mean = 3.86, CV = 29.88%) ranked twenty-eighth overall, reflecting its significance in economic feasibility assessments. Conversely, **Operating Cost of Glazing (Ec-1.2)** (RII = 0.573, mean = 3.00, CV = 44.72%) exhibited high variability and lower perceived importance, ranking forty-fourth overall, leading to its exclusion from the final framework.

Table 31: Summary of sub-criteria rankings analysis under economical dimension

Main Crite ria	Sub-criteria		RII	Importance Level	RII ranking	Overall ranking	Mean value	SD	CV (%)
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	0.86	Very High	1	8	4.52	0.98	21.6
	Ec-1.2	Operating cost of glazing	0.57	Moderate	5	44	3.00	1.34	44.7
	Ec-1.3	Savings in Air conditioning	0.86	Very High	1	8	4.52	0.60	13.3
	Ec-1.4	Payback Period (PBP)	0.73	High	4	28	3.86	1.15	29.8
	Ec-1.5	Cooling cost saving	0.82	Very High	3	17	4.33	1.02	23.4

4.3.3.5 Technical Sub-Criteria

Table 32 presents the ranking analysis of the Technical sub-criteria, assessing sub-criteria under Operational Efficiency (T-1). Among these, **Durability (T-1.5)** emerged as the highest-ranked sub-criterion within this category, securing the third position overall, with an RII of 0.909 and a mean of 4.55. The low CV of 16.25% indicates strong expert consensus on its significance in assessing smart glazing technologies. **Switching Time/Transition Speed (T-1.1)** (RII = 0.845, mean = 4.23, CV = 21.82%) followed, ranking fourteenth overall, highlighting its importance in evaluating the responsiveness of glazing transitions. Similarly, **Commercial Maturity Level (T-1.7)** (RII = 0.836, mean = 4.18, CV = 20.39%) ranked sixteenth overall, emphasizing its relevance in determining the readiness of smart glazing solutions for practical applications.

Conversely, **Degree of Transparency (T-1.2)** and **Actuation (T-1.3)**, both with an RII of 0.709 and a mean of 3.55, ranked thirty-second overall, indicating moderate importance. However, Degree of Transparency (CV = 32.25%) exceeded the threshold and was therefore excluded from the final framework. Similarly, **Resilience (T-1.6)** (RII = 0.718, mean = 3.59, CV = 34.01%) ranked thirty-first overall but also exceeded the CV threshold, leading to its exclusion. Among the lowest-ranked sub-criteria, **Energy/Power Requirement for Glazing State (T-1.4)** (RII = 0.591, mean = 2.95, CV = 33.81%)

demonstrated high variability and a low mean value, ranking forty-second overall, resulting in its exclusion from the final framework.

Table 32: Summary of sub-criteria rankings analysis under technical dimension

Main Criteria	Sub-criteria		RII	Importance Level	RII rank	Overall rank	Mean value	SD	CV (%)
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	0.84	Very High	2	14	4.2	0.92	21.8
	T-1.2	Degree of transparency	0.70	High	5	32	3.5	1.14	32.2
	T-1.3	Actuation	0.70	High	5	32	3.5	0.67	18.9
	T-1.4	Energy /Power requirement for glazing state	0.59	Moderate	7	42	2.9	1.00	33.8
	T-1.5	Durability	0.90	Very High	1	3	4.5	0.74	16.2
	T-1.6	Resilience	0.71	High	4	31	3.5	1.22	34.0
	T-1.7	Commercial maturity level	0.83	Very High	3	16	4.1	0.85	20.3

4.3.3.6 Comments and Feedback

As part of the questionnaire, respondents were invited to provide comments, suggestions, and feedback on the proposed criteria. This optional section aimed to gather insights on modifying existing criteria, proposing new ones, and identifying overlaps or redundancies among sub-criteria. Table 33 summarizes the comments and feedback received from respondents, the corresponding responses, and the actions taken in refining the final sustainability assessment framework.

Table 33: Summary of expert comments, revisions, and justifications

ID	Comments/Suggestions/Feedback	Response	Action
5	Difficult to separate out these elements as a good performing building will integrate as many aspects above as possible. An area missing is the embodied energy factor of a system also.	Embodied energy of glazing was considered but ranked lowest, leading to its exclusion.	Excluded from the final hierarchy.
5	A circular economy for materials is essential as there is not a finite amount available. Water ought to be the new 'gold' in terms of the respect industry gives it - it is an essential part of LIFE. Using less is more and weighing up the essential for the building and not wasted.	Circular economy was omitted as it extends beyond the study's scope, and water conservation was excluded due to low importance and high variability.	Circular economy not considered; water use excluded.
5	Natural light is required for good health and wellbeing of building occupants. The	Daylighting is considered and included , other factors	Not included in glazing assessment.

ID	Comments/Suggestions/Feedback	Response	Action
	orientation of the facade and site location matters in design. A collaborative approach is required with iterations to improve to the best possible outcome for the building designed.	are crucial but fall outside the glazing-specific scope of this study.	
5	Better outcomes if buildings are smaller rather than larger, designed for low consumption and occupant health in mind.	Acknowledged but beyond the study's glazing-specific focus.	Not applicable to glazing evaluation.
5	Need v demand. Or is a refurbished or reuse of structure/materials possible? Education of consumers is essential to reduce the never-ending greed factor.	Relevant to broader sustainability but not specific to glazing assessment.	Not applicable to glazing-specific evaluation.
7	Don't forget the environmental cost (search the keywords). Also the environmental impact (CO ₂ emissions equivalent).	Environmental costs are too broad to quantify at this stage, but CO ₂ emissions are addressed through mitigation measures.	Environmental costs excluded; CO ₂ emissions considered via mitigation factors.
9	Some sub-criteria describe more or less the same thing and it is difficult to assign importance to fine margins.	Redundancies were consolidated	Criteria refined to avoid redundancy.
14	If SHGC is included in the framework, sub-criteria such as Solar Transmittance, Solar Reflectance, and Solar Energy Absorption become redundant, as SHGC inherently accounts for these aspects.	SHGC was prioritized as a comprehensive measure, and redundant sub-criteria were removed.	Redundant sub-criteria removed.
14	Resilience, in the context of smart glazing, is generally tied to external factors like extreme weather events or physical impacts. While this may be important in specialized environments (e.g., hurricane-prone areas), it is not universally critical for assessing the sustainability of glazing in standard building applications and redundant to Durability.	Due to redundancy and contextual specificity, Resilience was removed.	Resilience excluded.
16	The selection of criteria seems very comprehensive, but I suggest reducing the number of criteria to make it more practical. Good luck.	High-ranking criteria were prioritized to improve applicability.	The framework was streamlined for practicality.

4.3.4 Summary and Final Criteria Hierarchy

The questionnaire analysis provided critical insights into the prioritization of sustainability criteria for evaluating smart glazing systems in non-domestic buildings within hot climatic regions. Experts assessed the importance of various criteria and sub-criteria across Environmental, Social, Economic, and Technical dimensions, using statistical metrics such as the Relative Importance Index (RII), mean values, standard deviation (SD), and

coefficient of variation (CV) (Table 28, Table 29, Table 30, Table 31, Table 32) to ensure consensus and identify the most relevant criteria for inclusion in the sustainability assessment framework. Some criteria and sub-criteria were excluded for failing to meet the statistical inclusion thresholds, while others were removed due to redundancy or the unavailability of quantitative or qualitative data for further assessment.

Three main criteria and 18 sub-criteria were removed based on the experts' judgement, corresponding to their lower statistical ranking. Some sub-criteria were excluded due to redundancy, as suggested by expert input. For example, Solar Heat Gain Coefficient (SHGC) was prioritized, leading to the removal of related sub-criteria such as Solar Transmittance, Solar Reflectance, and Solar Energy Absorption. Similarly, Resilience was removed due to both its high CV value and redundancy with Durability.

Beyond statistical thresholds, certain criteria were eliminated due to the unavailability of performance data required for further assessment. Notably, the Noise Reduction Index was removed despite its high importance rankings, as sufficient data was not available for evaluation.

In total, four main criteria and 20 sub-criteria were excluded from the earlier sustainability assessment hierarchy. This refined hierarchy, as shown in Table 34 ensures that only the most relevant, statistically supported, and practically assessable criteria are retained, providing a robust and applicable tool for selecting sustainable smart glazing solutions in hot climatic regions.

Table 34: Final sustainability criteria and sub-criteria identified through SLR

Sustainability dimension	Main criteria	Sub-criteria	
Environmental (En)	Energy Efficiency (En-1)	En-1.1	Energy consumption for heating
		En-1.2	Energy consumption for cooling
		En-1.3	Energy consumption for artificial lighting
		En-1.4	Total energy consumption (HVAC, lighting)
		En-1.5	Total energy savings
		En-1.8	CO ₂ mitigation
Social (S)	Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)
		S-1.3	Daylight Glare Index (DGI)
		S-1.4	Daylight Autonomy (DA)
		S-1.5	Daylight Factor (DF)
		S-1.6	Uniformity of daylight
		S-1.7	Useful Daylight Illuminance (UDI)
	Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)
		S-2.2	U-Value
		S-2.8	Predicted Mean Vote (PMV)
		S-2.9	Predicted Percentage of Dissatisfied (PPD)
		S-2.10	Annual window heat gain
		S-2.11	Indoor temperature
		S-2.12	Light-to-solar gain ratio (LSG)
	Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)
Economic (Ec)	Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost
		Ec-1.3	Total energy savings
		Ec-1.4	Payback Period (PBP)
		Ec-1.5	Cooling cost saving
Technical (T)	Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed
		T-1.3	Actuation
		T-1.4	Energy power requirement for the glazing state
		T-1.5	Durability
		T-1.7	Commercial maturity level

4.4 Selected Alternatives of Smart Glazing

In alignment with the study's focus on smart glazing systems, a comprehensive literature review and experts' suggestions led to the identification of numerous potential smart glazing alternatives for buildings commonly used in hot climatic regions, as discussed in

the Literature review. However, considering the specific research objective and the need to focus on commercially available smart glazing technologies for non-domestic buildings, this study narrows its scope to **Seven** smart glazing alternatives: **Electrochromic (EC)**, **Polymer Dispersed Liquid Crystal (PDLC)**, **Suspended Particle Device (SPD)**, **Thermochromic (TC)**, **Thermotropic (TC)**, **photochromic** and **SPD glazing** as presented in Table 35.

Table 35: Selected smart glazing alternatives

Sr. no	Alternative	ID	Thickn ess	Manufactur er/ Supplier	SHGC	U-value	VLT	Reff.
			(mm)		Tinted /Opaque	W/m²K	Tinted /Opaque	
1	Base case	A	---	Existing	0.8	5.5	0.8	Existing
2	Electrochromic (EC)	A7	07	SAGE	0.18	3.523	0.014	Energy plus database
3	Polymer Dispersed Liquid Crystal (PDLC)	A1	08	Literature (Laminated)	0.317	5.646	0.38	[115]
4	Suspended Particle Device (SPD)	A8	08	Literature (Laminated)	0.05	5.9	0.05	[38, 116]
5	Thermochromic (TC)	A6	07	LBNL	0.499	5.7	0.086	Energy plus database
6	Thermotropic (TT)	A9	09	Fraunhofer IAP	0.59	5.74	0.46	[46, 117]
7	Photochromic (PC)	A10	08	Literature (Laminated)	0.44	5.81	0.11	[49]
8	Gassochromic (GC)	A4	06	Literature	0.52	2.6	0.54	[72]

These technologies represent a spectrum of smart glazing solutions, each with distinct characteristics and potential benefits in terms of energy efficiency, occupant comfort, and environmental sustainability. The selection of these alternatives is based on their prevalence in the market, technological maturity, and their potential to address the unique challenges of hot climates, thereby ensuring the practical relevance and applicability of the developed sustainability assessment framework. The earlier section in the chapter provides

a detailed description of each investigated smart glazing alternative and Table 35 presents the final selected alternatives of smart glazing systems.

4.5 Hierarchical Model

Hierarchical model (**Figure 30**): The model comprises three layers: the Objective Layer (L1), the Dimensional Layer (L2), and the Alternative Layer (L3).

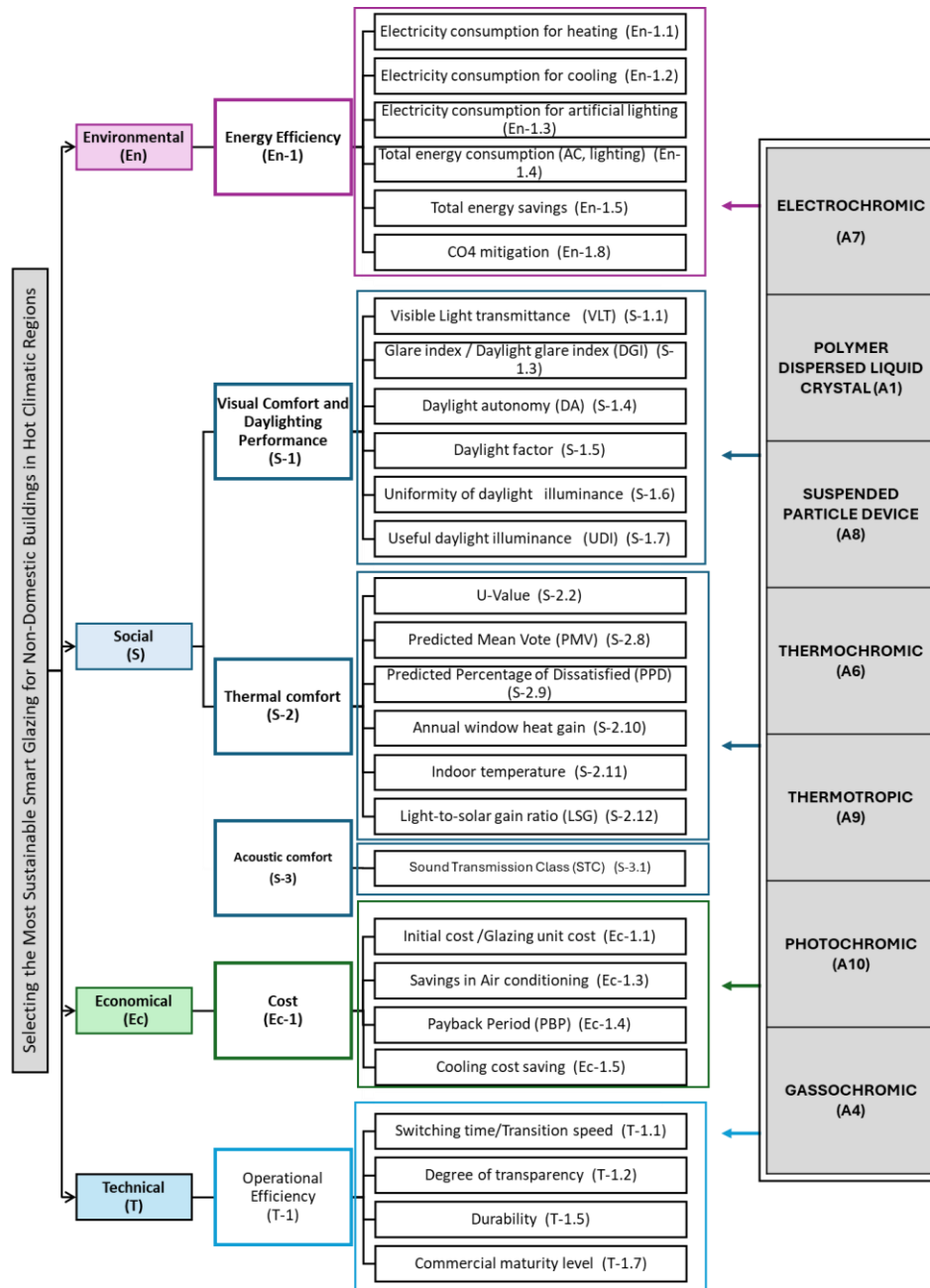


Figure 30: Experts' validated hierarchy

4.6 Data Collection Results

4.6.1 Calibration of the Model

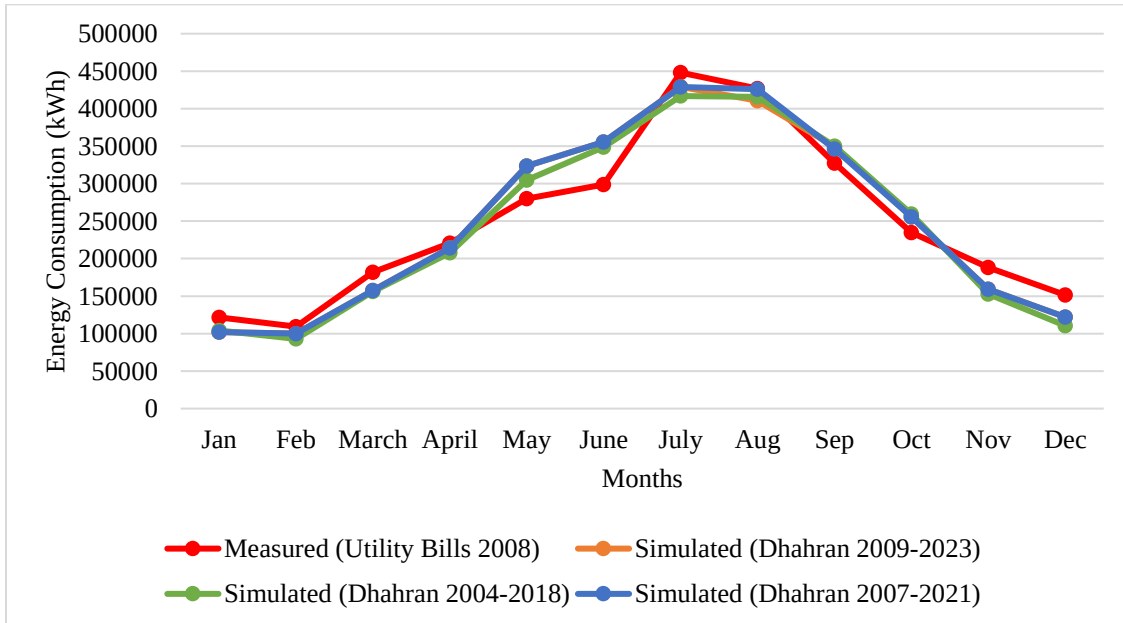
The calibration process involved comparing the simulated monthly energy consumption values with actual **utility bills from 2008** to ensure the accuracy of the simulation model. The model was tested using three different weather datasets for Dhahran spanning different periods: 2009–2023, 2004–2018, and 2007–2021. The validation was performed using Normalized Mean Bias Error (NMBE) and Coefficient of Variation of the Root Mean Square Error (CVRMSE), by ASHRAE Guideline 14 standards.

The measured and simulated monthly energy consumption values are presented in Figure 31, illustrating the alignment between each simulation and the actual utility data. These comparisons are further detailed in Table 36, which explicitly presents the monthly energy consumption values and corresponding calibration metrics. A comprehensive analysis of calibration accuracy metrics is shown in Figure 32, highlighting model performance relative to established ASHRAE Guideline 14 standards.

The model utilizing the **Dhahran 2007–2021 weather dataset** yielded the most accurate results, achieving an NMBE of 0.69% and a CVRMSE of 11.63%, both well within the acceptable calibration thresholds defined by ASHRAE Guideline 14 ($\text{NMBE} \leq \pm 5\%$ and $\text{CVRMSE} \leq 15\%$ for monthly calibration). In contrast, the model using the Dhahran 2009–2023 dataset resulted in $\text{NMBE} = -4.59\%$ and $\text{CVRMSE} = 11.87\%$, also meeting ASHRAE limits but exhibiting slightly higher deviations. The Dhahran 2004–2018 dataset, however, exhibited the highest deviation ($\text{NMBE} = -29.27\%$), exceeding the acceptable bias limit, making it unsuitable for accurate energy consumption predictions.

Table 36: Measured vs. simulated monthly energy consumption and calibration metrics

Measured (kWh)		Simulated (kWh)		
Months	Utility bills (2008)	Dhahran 2009-2023	Dhahran 2004-2018	Dhahran 2007-2021
(n = 12)	R	p	p	p
Jan	121648	102177.2	104079.8	102177.2
Feb	109326	100076.3	92939.44	100076.3
March	182010	157399.1	156348.8	157399.1
April	220621	214321.7	207756.6	214321.7
May	279870	323745.1	304829.2	323745.1
June	298713	355562.3	348731	355562.3
July	448070	429042	416845.5	428945.3
Aug	427023	410674.3	415837.5	426012.4
Sep	327606	349035.9	349872.3	346265.6
Oct	234775	255473.6	259675	255531.4
Nov	188362	159155.7	152767.4	159155.7
Dec	151483	121953.5	110395.7	121953.5
Mean of Measured Values ($\bar{r}$)	237179.7			
NMBE		-4.59181	-29.2741	0.69
CVRMSE		11.86855	11.98531	11.63457

**Figure 31:** The model's measured versus simulated monthly energy consumption after calibration

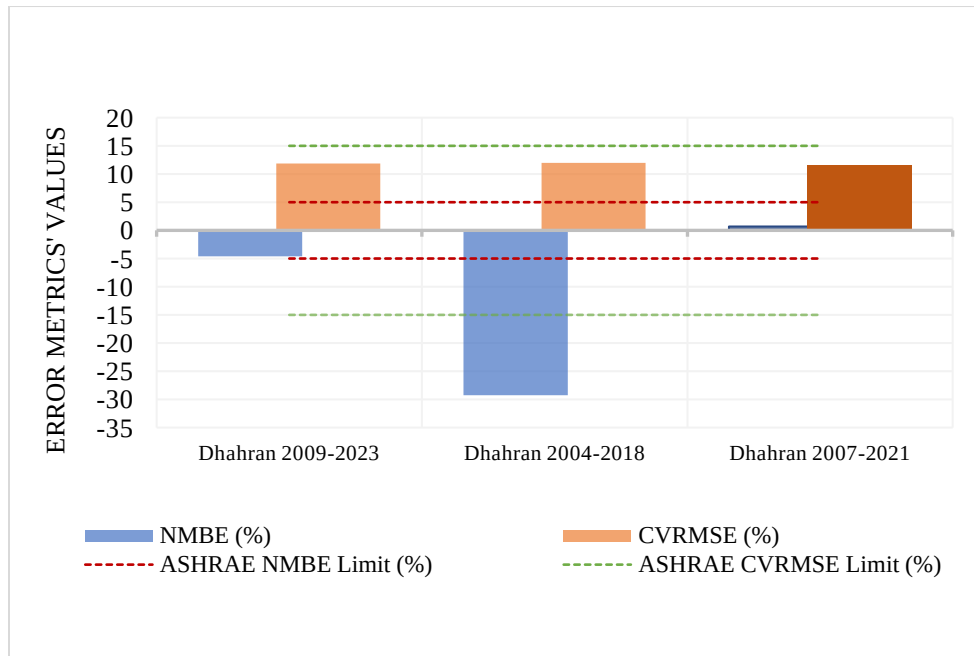


Figure 32: CVRMSE and NMBE values compared to ASHRAE limits

4.6.2 Environmental Performance Results

4.6.2.1 Energy Efficiency Performance Results (En-1)

This section presents the simulation-based energy performance results for each smart glazing alternative, focusing on heating, cooling, and artificial lighting energy consumption, total energy savings, and CO₂ mitigation. These parameters significantly influence building energy efficiency, particularly in hot climatic regions such as Riyadh, and inform the comparative analysis of energy-efficient glazing alternatives. The baseline scenario represents a conventional clear glazing system, which is compared against the eight smart glazing alternatives to determine the potential improvements in energy efficiency. The results, presented in Table 37, illustrate the energy performance of each smart glazing alternative in terms of:

- Heating energy demand (district heating)
- Cooling energy demand (district cooling)

- Artificial lighting energy consumption
- Total energy consumption (Heating + Cooling + lighting)
- Total energy savings (%) relative to the baseline
- CO₂ mitigation (%)

Table 37: Annual energy consumption and savings for smart glazing alternatives (KWh/yr)

Energy Efficiency (Env-1)			Smart glazing alternatives								
Sub-Criteria	Unit	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Avg.	SD (%)
		A	A7	A1	A8	A6	A9	A10	A4		
Energy consumption for heating	KWh/yr	209768	236498	249236	<u>283632</u>	230462	224037	236193	<u>203964</u>	237717	10.3
Energy consumption for cooling	KWh/yr	5068419	4541090	4640819	<u>4390353</u>	4842666	<u>4898593</u>	4780974	4756126	4692946	3.8
Energy consumption for artificial lighting	KWh/yr	20655	<u>38148</u>	21089	33752	31787	20944	27437	<u>20850</u>	27715	25.5
Total energy consumption	KWh/yr	5298843	4815736	4911145	<u>4707738</u>	5104916	<u>5143576</u>	5044605	4980941	4958380	3.2
Total energy savings	KWh/yr	---	<u>483106</u>	387697.7	591104	193926	<u>155266</u>	254237	317901	340463	46.3
	%	---	<u>10.03</u>	7.89	12.56	3.80	<u>3.02</u>	5.04	6.38	7.0	49.5
CO2 emissions	Kg/year	2680684	2436281	2484548	2381644	2582577	<u>2602135</u>	2552066	2519858	2508444	3.2
CO2 mitigation	Kg/year	---	244403	196136	<u>299039</u>	98107	<u>78549</u>	128618	160826	172240	46.3
• Minimum (Lowest value among alternatives): <u>x x x x</u> • Maximum (Highest value among alternatives): <u>x x x x</u>											

Table 38: Annual energy consumption per m²

Energy Efficiency (Env-1)		Per m2 of floor Area								Per m2 of glazing area							
Sub-Criteria	Unit	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Base case	EC	PDLC	SPD	TC	TT	PC	GC
		A	A7	A1	A8	A6	A9	A10	A4	A	A7	A1	A8	A6	A9	A10	A4
Energy consumption for heating	KWh/yr/m2	25	28	30	34	27	27	28	24	118	134	141	160	130	127	133	115
Energy consumption for cooling		603	541	552	523	577	583	569	566	2863	2565	2621	2480	2735	2767	2700	2686
Energy consumption for artificial lighting		2	5	3	4	4	2	3	2	12	22	12	19	18	12	15	12
Total energy consumption		631	573	585	560	608	612	601	593	2993	2720	2774	2659	2883	2905	2849	2813
Total Energy savings		%	---	10	8	13	4	<u>3</u>	5	6	---	10	8	13	4	<u>3</u>	5
CO2 emissions	Kg/yr/m2	319	290	296	284	307	310	304	300	1514	1376	1403	1345	1459	1470	1441	1423
CO2 mitigation	yr/m2	---	29	23	36	12	9	15	19	---	138	111	169	55	44	73	91

a) Heating Energy Consumption (En-1.1)

Heating energy consumption is directly influenced by the thermal transmittance (U-value) and solar heat gain coefficient (SHGC) of glazing systems. The base case (6 mm clear glass) exhibited an annual heating demand of 209,768 kWh/year, serving as a reference for comparative analysis. Among the smart glazing alternatives, SPD glazing (A8) recorded the highest heating demand, increasing by 35.2% to 283,632.77 kWh/year compared to the base case., followed by PDLC (A1) at 249,236.02 kWh/year, Electrochromic (A7) at 236,497.94 kWh/year, and Thermotropic (A9) at 224,037.47 kWh/year. These increases are attributed to reduced passive solar heat gain, necessitating greater reliance on heating systems.

Conversely, Gasochromic (A4) exhibited the lowest heating demand at 203,964.6 kWh/year, reflecting a 2.8% reduction relative to the base case, followed by Photochromic (A10) at 236,193.89 kWh/year and Thermochromic (A6) at 230,462.12 kWh/year, which showed moderate reductions. However, overall, smart glazing did not contribute to reducing heating energy demand. Instead, most options increased heating consumption in the hot climatic region of Riyadh, Saudi Arabia, due to reduced passive solar heat gain. Figure 33 illustrates the variations in heating energy consumption among the alternatives.

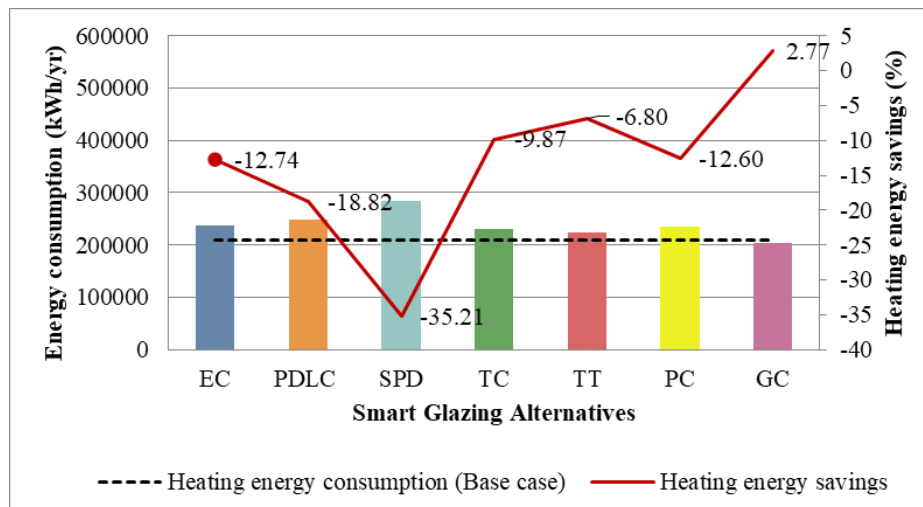


Figure 33: Heating energy consumption (KWh/yr) for smart glazing alternatives

b) Cooling Energy Consumption (En-1.2)

Cooling energy demand, which constitutes the largest share of total energy consumption in hot climates, was significantly influenced by the choice of smart glazing. The base case exhibited an annual cooling energy consumption of 5,068,420 kWh/year, serving as a benchmark for evaluating cooling efficiency across the smart glazing alternatives.

The introduction of smart glazing led to varying levels of cooling energy savings. SPD glazing (A8) demonstrated the highest reduction, decreasing cooling energy consumption by 13.37% to 4,390,353 kWh/year compared to the base case. Electrochromic (A7) and PDLC (A1) followed with reductions of 10.39% and 8.44%, respectively, showcasing their effectiveness in mitigating cooling loads. Conversely, Thermotropic (A9) exhibited the lowest reduction in cooling energy demand at just 3.37%, underscoring its limited impact on cooling efficiency. Photochromic (A10) and Gasochromic (A4) achieved moderate reductions of 4.80% and 6.00%, respectively, balancing solar control with energy savings.

These results highlight the variations in cooling performance among the glazing alternatives, demonstrating that dynamic glazing technologies offer the most substantial

reductions in cooling energy demand. **Figure 34** presents a comparative visualization of cooling energy consumption, illustrating the efficiency of different smart glazing alternatives and their relative contributions to cooling energy savings.

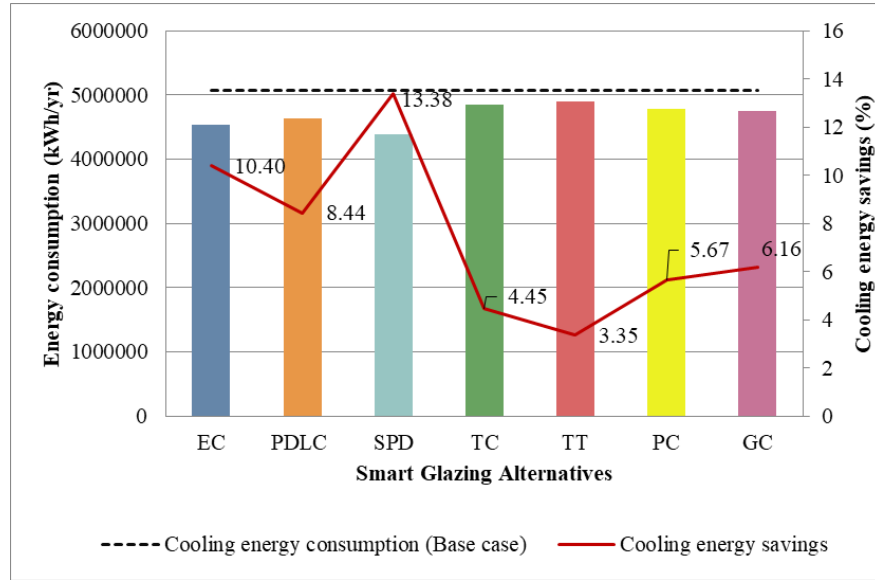


Figure 34: Cooling energy consumption (kWh/yr) for smart glazing alternatives

c) Artificial Lighting Energy Consumption (En-1.3)

Artificial lighting energy consumption is primarily influenced by visible light transmittance (VLT), which determines the extent of daylight penetration into indoor spaces. The base case exhibited an annual artificial lighting demand of 20,655.34 kWh/year, serving as a reference for assessing the impact of different glazing alternatives on lighting energy use. Among the smart glazing alternatives, Electrochromic (A7) recorded the highest artificial lighting demand, increasing by 84.8% compared to the base case. SPD (A8) and Thermochromic (A6) also exhibited substantial increases of 63.4% and 53.9%, respectively, illustrating the trade-off between improved solar control and reduced daylight penetration.

Conversely, Gasochromic (A4) demonstrated the lowest increase in artificial lighting demand, at just 0.9% above the base case, highlighting its well-balanced approach to light transmittance and energy efficiency. Photochromic (A10) and Thermotropic (A9) exhibited moderate increases of 32.8% and 4.8%, respectively, suggesting a balance between daylight utilization and solar control. These findings underscore the importance of selecting glazing solutions that maximize daylight availability while minimizing artificial lighting demand. Figure 35 illustrates the variations in artificial lighting demand across different smart glazing alternatives.

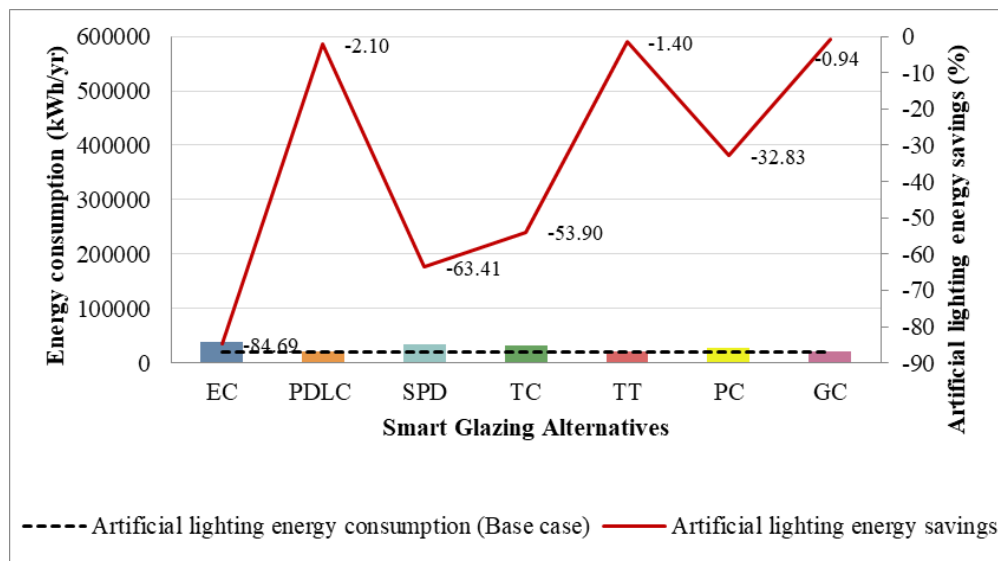


Figure 35: Artificial energy consumption (kWh/yr) for smart glazing alternatives

d) Total Energy Consumption and Savings (En-1.4 & En-1.5)

Total energy consumption, accounting for heating, cooling, and artificial lighting, was the highest in the base case at 5,298,843 kWh/year, serving as the reference point for comparative analysis. Among the smart glazing alternatives, Thermotropic (A9) exhibited the highest energy consumption, reaching 5,143,576.17 kWh/year (a 3.02% total energy saving compared to the base case), followed closely by Thermochromic (A6) at

5,104,916.47 kWh/year (a 3.80% reduction in energy consumption), indicating their limited effectiveness in reducing building's energy consumption.

SPD (A8) achieved the highest total energy savings, reducing energy consumption by 12.56% relative to the base case, followed by Electrochromic (A7) (10.06%) and PDLC (A1) (7.89%), demonstrating their superior energy efficiency potential. Photochromic (A10) and Gasochromic (A4) exhibited moderate savings of 5.04% and 6.38%, respectively, balancing daylighting performance with energy conservation.

Figure 36 presents a comparative analysis of total energy consumption across all glazing alternatives, highlighting the highest, lowest, and mid-range performers, as well as their relative energy-saving potential.

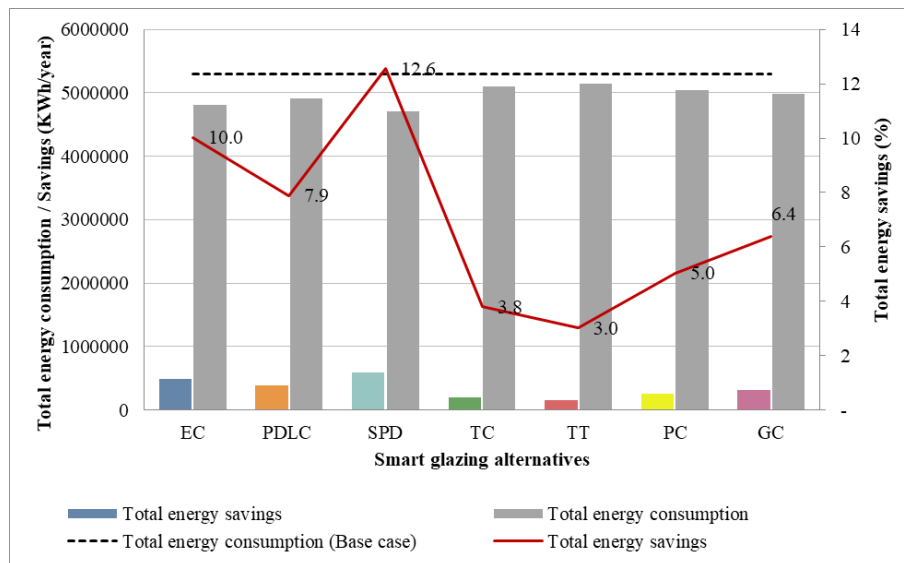


Figure 36: Total energy consumption (kWh/yr) for smart glazing alternatives

e) CO₂ Mitigation Potential (En-1.6)

Annual CO₂ mitigation was calculated based on total energy savings (kWh), specifically considering reductions in heating, cooling, and lighting energy consumption relative to the baseline scenario. Using the CO₂ emission factor of 0.5059 kgCO₂/kWh specific to the

Saudi Arabian electricity grid, the following results were obtained as mentioned in Table 37 and Figure 37.

The highest CO₂ mitigation was achieved by Suspended Particle Device (SPD) glazing, with an annual reduction of 299,039.8 kg/year (12.56%), primarily due to substantial total energy savings. This was followed by Electrochromic (EC) glazing with a reduction of 244,403.6 kg/year (10.03%), and Polymer Dispersed Liquid Crystal (PDLC) glazing at 196,136.3 kg/year (7.89%).

Moderate CO₂ reductions were observed with Gasochromic (GC) glazing at 160,826.4 kg/year (6.38%), Photochromic (PC) glazing at 128,618.7 kg/year (5.04%), and Thermochromic (TC) glazing at 98,107.4 kg/year (3.80%). The lowest CO₂ mitigation was noted for Thermotropic (TT) glazing, reducing emissions by 78,549.5 kg/year (3.02%).

Figure 37 clearly illustrates the variations in CO₂ emissions and the corresponding mitigation percentages achieved by each smart glazing alternative. These findings highlight the environmental benefits of adopting smart glazing technologies, particularly the significant impact of SPD glazing in reducing the building's carbon footprint in hot climatic regions.

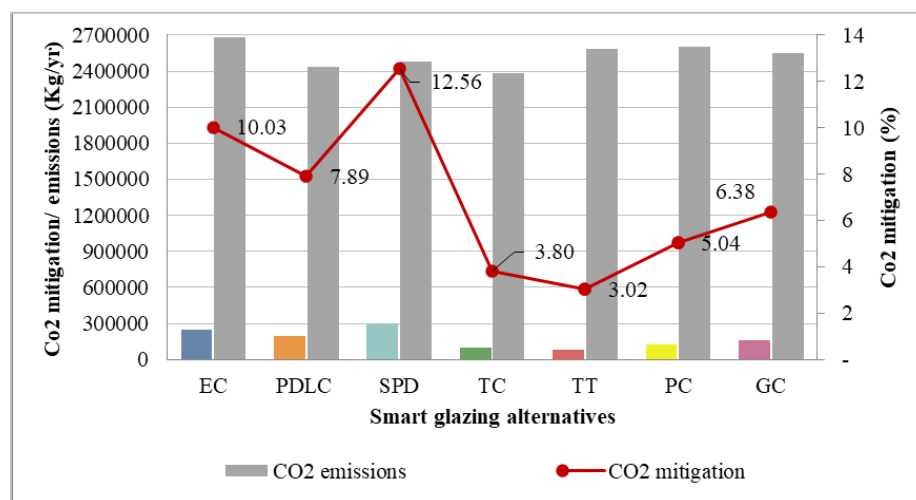


Figure 37: CO₂ Emissions and mitigation potential for smart glazing alternatives

4.6.2.2 Summary of Environmental Performance

The environmental sustainability assessment of smart glazing alternatives, based on energy efficiency indicators, revealed distinct differences in the energy efficiency of smart glazing alternatives in a hot-climate context. While heating and lighting demands increased in several cases, cooling energy savings emerged as the most influential factor in overall energy reduction and CO₂ mitigation. Among the alternatives, SPD glazing achieved the highest environmental performance, with 12.56% total energy savings and 299,039.8 kg/year of CO₂ mitigation, followed by Electrochromic and PDLC glazing.

Gasochromic and Photochromic offered moderate environmental benefits, while Thermochromic and Thermotropic were the least effective in reducing energy consumption and emissions. Table 39 presents the environmental ranking based on total energy savings and CO₂ mitigation.

It is important to note that this ranking serves a comparative purpose only. For integration into the Decision matrix for multi-criteria decision-making (MCDM) framework, the actual simulation-derived performance values from Table 37, including annual energy use and CO₂ emissions are used as inputs. These values will be combined with technical, economic, and social indicators to ensure a comprehensive sustainability assessment of smart glazing systems.

Table 39: Environmental sustainability ranking of smart glazing alternatives

Rank	Smart Glazing Alternative	Total Energy Savings		CO ₂ Mitigation
		<i>KWh/year</i>	<i>(%)</i>	<i>Kg/Year</i>
1	SPD (A8)	591104.5	12.56	299039.8
2	Electrochromic (A7)	483106.6	10.03	244403.6
3	PDLC (A1)	387697.7	7.89	196136.3
4	Gasochromic (A4)	317901.6	6.38	160826.4

Rank	Smart Glazing Alternative	Total Energy Savings		CO ₂ Mitigation
		<i>KWh/year</i>	<i>(%)</i>	<i>Kg/Year</i>
5	Photochromic (A10)	254237.5	5.04	128618.7
6	Thermochromic (A6)	193926.5	3.80	98107.4
7	Thermotropic (A9)	155266.8	3.02	78549.5
	Average	340463.0	6.96	172240.2
	SD (%)	46.3%	49.5%	46.3%

4.6.3 Social Performance Results

4.6.3.1 Visual Comfort and Daylighting Results

In hot climates, abundant sunlight can provide ample daylight but also cause glare and overheating. Managing daylight is critical for indoor environmental quality as insufficient daylight or excessive glare both lead to visual discomfort [173]. This section presents the simulation results evaluating the visual comfort and daylighting performance of seven smart glazing alternatives: Electrochromic (EC), Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Thermochromic (TC), Thermotropic (TT), Photochromic (PC), and Gasochromic (GC). The analysis was conducted for a non-domestic office building in a hot-dry climate (Riyadh, Saudi Arabia) using the daylighting module of DesignBuilder (v7.3.0.40) with Radiance simulation. The simulations focus specifically on the fully tinted/opaque state of each glazing type to compare how each smart glazing, when tinted, impacts daylight availability and visual comfort.

In this study, multiple daylighting indicators like Daylight Factor (DF), Useful Daylight Illuminance (UDI), and Spatial Daylight Autonomy (sDA) were intentionally selected to provide a comprehensive and complementary assessment of daylighting and visual comfort. While some overlap may appear, each metric addresses a unique aspect of daylight performance. DF offers a static benchmark under overcast conditions, useful for early-stage analysis. UDI captures illuminance levels within a useful range throughout the year,

offering granularity on daylight usability. sDA, aligned with LEED v4.1, evaluates task-based daylight sufficiency. Their integration supports a robust methodology that addresses both daylight sufficiency and glare control, enabling balanced design decisions for occupant comfort in hot, sunny climates.

The results are presented across the following six key visual comfort and daylighting performance sub-criteria:

- Visible Light Transmittance (VLT) (Soc-1.1)
- Daylight Glare Index (DGI) (Soc-1.2)
- Daylight Autonomy (DA) (Soc-1.3)
- Uniformity of Daylight Illuminance (Soc-1.5)
- Useful Daylight Illuminance (UDI) (Soc-1.6)
- Daylight Factor (Soc-1.4)

a) Visible Light Transmittance (VLT) (Soc-1.1)

Visible Light Transmittance (VLT) quantifies the proportion of visible daylight transmitted through a glazing system, measured on a scale from 0% (opaque) to 100% (completely transparent). This parameter is critical for evaluating the optical clarity, daylight availability, and potential for glare control in buildings, significantly impacting occupant comfort, productivity, and energy efficiency, especially in commercial office settings. Typically, optimal VLT values for commercial offices range from 40% to 70% to maintain an adequate balance between daylight access and glare mitigation [215].

Smart glazing technologies offer dynamic control over visible light transmission (VLT) to balance daylight provision and glare control [173]. This study evaluated the VLT of fully tinted/opaque states of seven smart glazing alternatives to assess their impact on daylight

availability and potential glare control performance. Table 40 summarizes the VLT values for each glazing type evaluated.

Table 40: Visible Light Transmittance of smart glazing alternatives in fully tinted state

Smart glazing alternative	ID	VLT	Reference
		<i>Tinted /Opaque</i>	
Base case	A	0.8	Existing
Electrochromic (EC)	A7	0.014	Energy plus database
Polymer Dispersed Liquid Crystal (PDLC)	A1	0.38	[115]
Suspended Particle Device (SPD)	A8	0.05	[38, 116]
Thermochromic (TC)	A6	0.086	Energy plus database
Thermotropic (TC)	A9	0.46	[46, 117]
Photochromic (PC)	A10	0.11	[49]
Gassochromic (GC)	A4	0.54	[72]

The findings highlight substantial variations, indicating clear differences in their ability to manage daylight (Table 40). Electrochromic glazing exhibited the lowest VLT at 1.4%, demonstrating excellent glare reduction but severely restricting daylight entry. Conversely, Gasochromic glazing had the highest VLT (54%), ensuring ample daylight transmission even when tinted. Intermediate performance was observed for PDLC (38%) and Thermotropic glazing (46%). SPD (5%), Thermochromic (8.6%), and Photochromic (11%) provided significantly lower daylight transmission, emphasizing glare control at the potential cost of adequate daylight.

b) Daylight Glare Index (DGI) (Soc-1.2)

The Daylight Glare Index (DGI) quantifies discomfort glare caused by daylight within indoor environments. The results indicated that Zone 4 of floor 7 exhibited the highest DGI values, which will be used further for comparative analysis. Table 41 presents monthly average DGI values for floor 7, zone 4, representing the area with peak glare conditions

identified from simulation results. Moreover, Figure 38 provides a comprehensive overview of the average glare index fluctuations resulting from different smart glazing alternatives.

The results indicated that the base case consistently produced high glare indices across the year, peaking in June at a DGI of 14.16, indicating uncomfortable glare conditions during peak summer months. Electrochromic glazing significantly reduced glare levels, with the highest monthly value of only 2.89 in June, signifying exceptional glare control capability. Suspended Particle Device (SPD) glazing also reduced glare substantially (DGI of 7.01 in June), while Photochromic and Thermochromic glazing presented moderate glare reductions. Conversely, Gasochromic and Thermotropic glazing exhibited relatively higher glare indices (13.24 and 12.92 in June, respectively), correlating with their higher VLT values. However, all the glare indices are ≤ 16 and are just imperceptible. Moreover, the findings from this assessment (for Floor 7, Zone 4, and for June month) will serve as input for the decision matrix.

Table 41: Glare index for floor 7 zone 4

Smart glazing alternatives	Base case	EC	PDLC	SPD	TC	TT	PC	GC
Jan	10.7	1.1	9.1	4.3	5.4	9.6	6.3	9.8
Feb	11.3	1.4	9.7	4.7	5.8	10.1	6.8	10.4
Mar	11.9	1.8	10.3	5.4	6.5	10.7	7.5	11.0
Apr	13.4	2.2	11.6	6.2	7.4	12.1	8.5	12.4
May	13.7	2.6	12.1	6.7	7.9	12.5	9.0	12.8
Jun	14.2	2.9	12.5	7.0	8.2	12.9	9.4	13.2
Jul	14.1	2.8	12.4	6.9	8.1	12.8	9.2	13.1
Aug	13.6	2.4	11.8	6.4	7.6	12.3	8.7	12.6
Sept	12.8	1.9	11.0	5.7	6.8	11.5	8.0	11.8
Oct	11.4	1.5	9.8	5.0	6.1	10.2	7.0	10.5
Nov	10.7	1.1	9.1	4.3	5.3	9.5	6.3	9.8
Dec	10.6	1.0	9.0	4.1	5.2	9.4	6.2	9.6

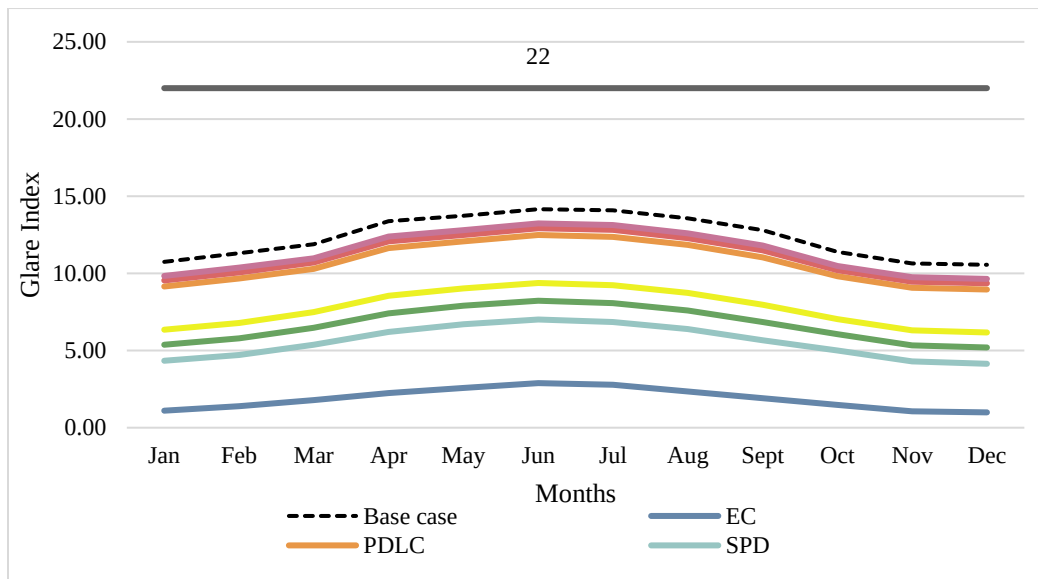


Figure 38: Simulated glare index value for smart glazing alternatives

c) Daylight Autonomy (DA) (Soc-1.3)

The spatial daylight autonomy results (sDA300lx, 50%) reflect the percentage of each floor zone receiving at least 300 lux of daylight for at least 50% of the annual occupied hours. Table 42 summarizes the area-weighted sDA results across all zones for each smart glazing alternative. The analysis followed the LEED v4.1 daylight criteria, which awards 1, 2, or 3 points when sDA values reach 40%, 55%, and 75%, respectively (Table 15).

Table 42 presents results for each analyzed zone and area-weighted average sDA300lx values obtained through DesignBuilder simulations. The base case achieved the highest daylight autonomy, with a weighted sDA of 63.11%, qualifying for 2 LEED daylighting points. Among smart glazing options, Thermotropic (TT) and Gasochromic (GC) glazings showed moderate daylight performance, with sDA values of 48.69% and 52.78%, respectively, both approaching the 2-point threshold. PDL glazing achieved a modest sDA of 43.41%, qualifying for 1 LEED point.

In contrast, Electrochromic (EC), SPD, Thermochromic (TC), and Photochromic (PC) glazings demonstrated poor daylight autonomy, with values ranging from 1.27% to 7.94%. These systems, although beneficial in reducing solar heat gain and glare, significantly limited visible light transmission, resulting in lower daylight availability. Furthermore, the weighted average sDA_{300lx} listed in Table 42 will be used in the decision matrix.

Table 42: Spatial daylight autonomy of smart glazing alternatives compared to base case

Floor	Zone	Floor Area (m ²)	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Min. sDA	Max. sDA
Ground	2	314.2	84.2	1.5	66.3	0.0	0.4	72.1	8.2	75.7	0.0	75.7
	1	314.8	85.7	0.0	69.7	3.2	10.3	74.6	19.5	77.5	0.0	77.5
Mezzanine	3	212.6	59.0	1.2	30.8	0.0	0.0	37.5	2.5	42.9	0.0	42.9
	1	227.8	61.5	1.4	36.1	1.3	4.5	42.2	7.4	47.5	1.3	47.5
	3	149.7	70.7	4.1	45.3	4.6	10.9	50.7	16.5	56.0	4.1	56.0
First	1	102.8	87.2	4.9	72.0	1.7	9.1	77.3	17.1	81.4	1.7	81.4
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	65.1	0.0	36.6	0.0	0.0	42.2	0.5	47.6	0.0	47.6
	2	102.6	87.0	6.6	69.3	0.0	0.4	76.3	9.1	79.9	0.0	79.9
Second	3	149.7	70.7	0.0	46.2	5.5	12.6	52.4	16.8	56.7	0.0	56.7
	1	102.8	87.6	4.9	71.3	1.7	8.9	77.9	17.0	81.0	1.7	81.0
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	65.4	0.0	36.7	0.0	0.0	42.8	4.4	48.0	0.0	48.0
	2	102.6	86.8	6.7	68.5	0.0	0.4	75.8	8.8	79.9	0.0	79.9
	3	149.7	70.7	0.0	46.2	5.5	12.6	52.4	16.8	56.7	0.0	56.7
	1	102.8	84.0	4.7	63.2	1.8	7.3	70.7	14.0	75.5	1.8	75.5
Third	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	65.4	0.0	36.7	0.0	0.0	42.8	4.4	48.0	0.0	48.0
	2	102.6	83.3	4.2	60.3	0.0	0.0	67.6	6.7	74.1	0.0	74.1
	3	149.7	70.7	0.0	46.2	5.5	12.6	52.4	16.8	56.7	0.0	56.7
Fourth	1	102.8	83.0	4.9	61.3	1.7	6.0	67.3	10.1	72.7	1.7	72.7
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	65.4	0.0	36.7	0.0	0.0	42.8	4.4	48.0	0.0	48.0
	2	102.6	81.6	1.7	57.3	0.0	0.0	64.4	3.0	70.5	0.0	70.5
Fifth	3	511.6	91.2	0.0	65.1	1.6	4.8	73.5	9.9	79.8	0.0	79.8
	1	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	149.7	53.4	4.0	32.0	3.9	8.3	36.1	11.3	39.9	3.9	39.9
Sixth	1	102.8	83.0	4.9	61.3	1.7	6.0	67.3	10.1	72.7	1.7	72.7
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	65.4	0.0	36.7	0.0	0.0	42.8	4.4	48.0	0.0	48.0
	2	102.6	81.6	1.7	57.3	0.0	0.0	64.4	3.0	70.5	0.0	70.5
Seventh	3	149.7	52.4	1.3	30.5	0.0	1.8	35.0	7.2	39.1	0.0	39.1
	1	102.8	83.0	4.9	61.3	1.7	6.0	67.3	10.1	72.7	1.7	72.7
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.6	47.7	0.0	25.3	0.0	0.0	30.0	2.5	33.8	0.0	33.8
	2	102.6	81.6	1.7	57.3	0.0	0.0	64.4	3.0	70.5	0.0	70.5
Total/ Weighted average		314.2	84.2	1.5	66.3	0.0	0.4	72.1	8.2	75.7	0.0	75.7
LEED4.1 points			2	0	1	0	0	1	0	1		

d) Useful Daylight Illuminance (UDI) (Soc-1.6)

Useful Daylight Illuminance (UDI) measures the percentage of occupied hours during which daylight levels remain within a range deemed comfortable for occupants. In this study, a range of 100–3000 lux was considered, where values below 100 lux are insufficient and values above 3000 lux may cause glare or thermal discomfort. UDI values were extracted from DesignBuilder simulations, and an area-weighted average was calculated across all zones for each glazing alternative. The area-weighted average UDI values in Table 43 will be used in the decision matrix.

The results, presented in Table 43 and visualized in Figure 39, show clear differences in daylight performance. Gasochromic (GC) glazing achieved the highest UDI (69.91%), followed closely by Thermotropic (TT) at 68.37%, indicating excellent daylighting performance with minimal glare risk. The Base case (66.76%) and PDLC glazing (66.24%) also performed strongly, demonstrating consistent daylight availability across zones.

By contrast, Electrochromic (EC) and SPD glazing exhibited significantly lower UDI values (6.10% and 13.32%, respectively), due to their low visible transmittance and strong solar control, which limit daylight entry. Thermochromic (TC) and Photochromic (PC) systems provided moderate daylight access, with UDI values of 29.61% and 37.23%, respectively.

Table 43: Average UDI_{100–3000 lux}, 50% for smart glazing alternatives

Floor	Zone	Floor Area (m ²)	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Min. UDI	Max. UDI
Ground	2	314.1	82.3	4.1	87.2	20.6	50.9	90.5	60.1	90.9	4.1	90.9
	1	314.7	74.0	9.9	86.7	30.3	56.2	86.7	64.2	85.8	9.9	86.7
Mezzanine	3	212.5	74.1	2.5	64.0	6.1	17.0	68.4	23.9	69.1	2.5	69.1
	1	227.8	70.4	6.3	67.0	10.2	21.9	68.0	29.0	72.0	6.3	72.0
	3	149.7	73.5	13.5	75.5	20.8	33.7	75.9	40.2	80.0	13.5	80.0
First	1	102.8	80.9	15.0	90.5	25.4	53.8	91.7	64.0	91.1	15.0	91.7
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0

Floor	Zone	Floor Area (m2)	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Min. UDI	Max. UDI
Second	4	149.5	83.0	3.4	70.6	10.8	22.1	77.4	29.5	79.9	3.4	79.9
	2	102.6	86.0	12.5	90.1	18.8	47.4	92.5	59.4	93.9	12.5	93.9
	3	149.7	73.4	11.8	73.8	20.7	33.9	74.3	40.2	78.8	11.8	78.8
	1	102.8	81.2	14.9	90.5	25.6	53.3	91.6	63.9	91.1	14.9	91.6
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	81.6	2.6	71.0	10.5	23.2	77.6	30.5	80.4	2.6	80.4
Third	2	102.6	85.6	12.5	90.1	18.5	47.3	91.9	60.0	93.6	12.5	93.6
	3	149.7	73.4	11.8	73.8	20.7	33.9	74.3	40.2	78.8	11.8	78.8
	1	102.8	80.2	12.8	86.6	21.2	45.0	88.4	55.5	88.0	12.8	88.4
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	81.6	2.6	71.0	10.5	23.2	77.6	30.5	80.4	2.6	80.4
	2	102.6	83.9	7.9	86.6	14.6	38.5	88.2	50.6	89.0	7.9	89.0
Fourth	3	149.7	73.4	11.8	73.8	20.7	33.9	74.3	40.2	78.8	11.8	78.8
	1	102.8	84.0	9.6	85.8	14.9	39.6	87.4	52.0	86.9	9.6	87.4
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	81.6	2.6	71.0	10.5	23.2	77.6	30.5	80.4	2.6	80.4
	2	102.1	88.7	4.4	84.5	9.0	33.2	87.1	46.2	88.5	4.4	88.5
	3	511.5	85.8	5.2	92.9	15.4	41.3	92.8	54.7	92.5	5.2	92.9
Fifth	1	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	149.7	64.4	8.7	59.1	14.3	23.1	60.0	27.9	67.9	8.7	67.9
	1	102.8	84.0	9.6	85.8	14.9	39.6	87.4	52.0	86.9	9.6	87.4
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	81.6	2.6	71.0	10.5	23.2	77.6	30.5	80.4	2.6	80.4
	2	102.6	88.7	4.4	84.5	9.0	33.2	87.1	46.2	88.5	4.4	88.5
Sixth	3	149.7	67.6	8.3	59.7	11.0	21.3	63.4	26.1	70.2	8.3	70.2
	1	102.8	84.0	9.6	85.8	14.9	39.6	87.4	52.0	86.9	9.6	87.4
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	81.6	2.6	71.0	10.5	23.2	77.6	30.5	80.4	2.6	80.4
	2	102.6	88.7	4.4	84.5	9.0	33.2	87.1	46.2	88.5	4.4	88.5
	3	149.7	67.6	8.3	59.7	11.0	21.3	63.4	26.1	70.2	8.3	70.2
Seventh	1	102.8	84.0	9.6	85.8	14.9	39.6	87.4	52.0	86.9	9.6	87.4
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	68.8	2.1	52.7	6.7	15.7	61.3	20.6	62.8	2.1	62.8
	2	102.6	88.7	4.4	84.5	9.0	33.2	87.1	46.2	88.5	4.4	88.5
Weighted Average UDI_{100 lux – 3000 lux} (%)			66.7	6.1	66.2	13.3	29.6	68.3	37.2	69.9	6.1	69.9

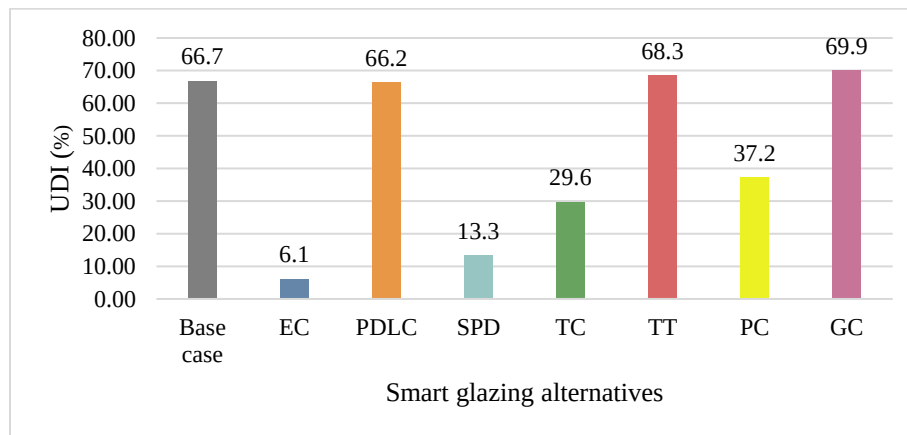


Figure 39: Weighted Average UDI_{100 lux – 3000 lux} (%)

e) Daylight Factor (Soc-1.4)

Daylight Factor (DF) is a standard index used to evaluate the daylight availability under overcast sky conditions [127]. According to BS 8206-2:2008, CIBSE Guide A, and Lighting Guide LG10, an average daylight factor of at least 2% is required in office spaces to ensure sufficient daylight availability, with a minimum-to-average uniformity ratio of at least 0.40 [103, 137].

In this study, DF simulations were carried out using DesignBuilder under overcast sky conditions. The zone-based daylight factors were calculated and then used to determine the area-weighted average DF for each smart glazing alternative across all occupied zones. These weighted averages were used for performance comparison and included in the decision matrix.

The results of the daylight factor analysis summarized in Table 44, indicated that the Base case achieved the highest daylight factor (7.88%), significantly above the 2% minimum threshold. Among the smart glazing options, Gasochromic (GC) (4.47%) and Thermotropic (TT) (3.71%) also exceeded the minimum DF requirement, providing sufficient daylight under overcast conditions. PDLC marginally met the criterion (2.98%). Conversely, Electrochromic (EC), SPD, Thermochromic (TC), and Photochromic (PC) glazing systems demonstrated substandard daylight penetration, with average DF values far below the minimum threshold.

Table 44: Daylight Factor (DF) for smart glazing alternatives

Floor	Zone	Floor Area (m ²)	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Min. DF	Max. DF
Ground	2	314.1	10.8	0.1	4.1	0.4	0.8	5.1	1.0	6.1	0.1	6.1
	1	314.7	16.5	0.1	6.3	0.6	1.2	7.8	1.5	9.4	0.1	9.4
Mezzanine	3	212.5	4.6	0.0	1.8	0.2	0.3	2.2	0.4	2.6	0.0	2.6

Floor	Zone	Floor Area (m2)	Base case	EC	PDLC	SPD	TC	TT	PC	GC	Min. DF	Max. DF
First	1	227.8	7.2	0.1	2.7	0.3	0.5	3.4	0.7	4.0	0.1	4.0
	3	149.7	7.1	0.1	2.5	0.2	0.4	3.2	0.6	3.9	0.1	3.9
	1	102.8	22.3	0.2	8.5	0.9	1.6	10.5	2.1	12.6	0.2	12.6
	5	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	2.4	0.0	0.9	0.1	0.2	1.2	0.2	1.4	0.0	1.4
Second	2	102.6	15.3	0.1	5.8	0.6	1.1	7.2	1.4	8.7	0.1	8.7
	3	149.7	7.3	0.1	2.7	0.2	0.5	3.3	0.6	4.0	0.1	4.0
	1	102.8	22.2	0.2	8.5	0.9	1.6	10.5	2.1	12.7	0.2	12.7
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	2.5	0.0	1.0	0.1	0.2	1.2	0.2	1.4	0.0	1.4
Third	2	102.6	15.3	0.1	5.8	0.6	1.1	7.2	1.4	8.7	0.1	8.7
	3	149.7	7.3	0.1	2.6	0.2	0.5	3.3	0.6	4.0	0.1	4.0
	1	102.8	18.6	0.2	7.1	0.7	1.3	8.8	1.8	10.6	0.2	10.6
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	2.5	0.0	1.0	0.1	0.2	1.2	0.2	1.4	0.0	1.4
Fourth	2	102.6	11.2	0.1	4.2	0.4	0.8	5.3	1.0	6.3	0.1	6.3
	3	149.7	7.3	0.1	2.6	0.2	0.5	3.4	0.6	4.0	0.1	4.0
	1	102.8	17.1	0.2	6.6	0.7	1.2	8.1	1.6	9.8	0.2	9.8
	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	2.5	0.0	1.0	0.1	0.2	1.2	0.2	1.4	0.0	1.4
Fifth	2	102.1	10.4	0.1	3.9	0.4	0.7	4.8	0.9	5.8	0.1	5.8
	3	511.5	9.5	0.1	3.6	0.4	0.7	4.5	0.9	5.4	0.1	5.4
	1	121.5	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	3	149.7	5.1	0.0	1.8	0.2	0.3	2.3	0.4	2.8	0.0	2.8
	1	102.8	17.2	0.2	6.6	0.7	1.2	8.2	1.6	9.9	0.2	9.9
Sixth	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	2.5	0.0	1.0	0.1	0.2	1.2	0.2	1.4	0.0	1.4
	2	102.6	10.3	0.1	3.9	0.4	0.7	4.8	0.9	5.8	0.1	5.8
	3	149.7	3.8	0.0	1.4	0.1	0.3	1.7	0.3	2.1	0.0	2.1
	1	102.8	17.2	0.2	6.6	0.7	1.2	8.2	1.6	9.8	0.2	9.8
Seventh	5	121.4	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0	0.0
	4	149.5	1.7	0.0	0.7	0.1	0.1	0.8	0.2	1.0	0.0	1.0
	2	102.6	10.3	0.1	3.9	0.4	0.7	4.8	0.9	5.8	0.1	5.8
Total/ Weighted average			7.88	0.07	2.98	0.29	0.55	3.71	0.72	4.47	0.07	4.47

f) Uniformity of Daylight (Soc-1.5)

The uniformity of daylight distribution was assessed using the Uniformity Daylight Factor (UDF), which is defined as the ratio of the minimum daylight factor to the average daylight

factor across the entire zone [216]. According to BREEAM 2.08 and the Building Research Establishment's Environmental Assessment Method, a UDF of at least 0.40 is required to ensure an efficient and visually comfortable working environment [130, 216].

In this study, UDF values were calculated under overcast sky conditions using DesignBuilder. For each glazing alternative, the minimum and average daylight factor values were obtained for every zone, and zone-level UDFs were determined accordingly. A building-wide, area-weighted average UDF was then calculated for each glazing type. These values are presented in Figure 40. The results clearly indicate that none of the evaluated glazing systems met the 0.40 threshold.

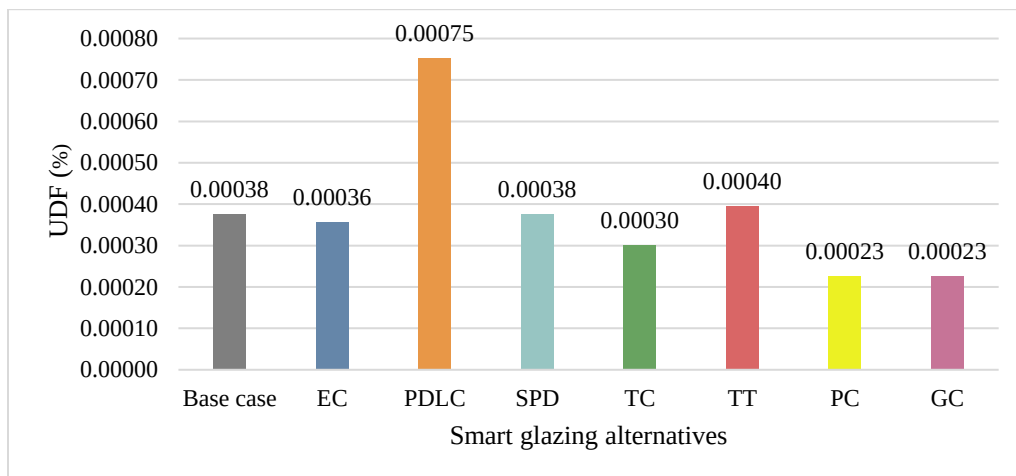


Figure 40: Weighted average Uniformity Daylight Factor (UDF) for smart glazing alternatives

4.6.3.2 Thermal Comfort (S-2)

a) Solar heat gain coefficient (SHGC) (S2.1)

The Solar Heat Gain Coefficient (SHGC) indicates the fraction of solar radiation transmitted through a glazing system, encompassing both directly transmitted and indirectly radiated heat [132]. Lower SHGC values are highly advantageous in hot climates like Riyadh, as they reduce cooling loads and enhance occupant thermal comfort. The

SHGC values for each of the smart glazing alternatives examined in this study are provided in **Table 45**.

Table 45: SHGC, U-value, and LSG values of smart glazing alternatives

Smart Glazing	ID	Manufacturer/ Supplier	VLT <i>Tinted /Opaque</i>	SHGC	U-value <i>W/m²K</i>	LSG	Reff.
Base case	A	Existing	0.881	0.819	5.5	1.076	Existing
EC	A7	SAGE	0.014	0.18	3.523	0.078	Energy Plus Database
PDLC	A1	Literature	0.38	0.317	5.646	1.199	[86]
SPD	A8	Literature	0.05	0.05	5.9	1	[33, 87]
TC	A6	LBNL	0.086	0.499	5.7	0.172	Energy Plus Database
TT	A9	Fraunhofer IAP	0.46	0.59	5.74	0.781	[88, 89]
PC	A10	Literature	0.11	0.44	5.81	0.250	[90]
GC	A4	Literature	0.54	0.52	2.6	1.038	[63]
		Min.	0.014	0.05	2.6	0.078	
		Max.	0.881	0.819	5.9	1.199	
SHGC: Solar Heat Gain Coefficient, U-value: Thermal Transmittance, VLT: Visible Light Transmittance, LSG: Light to solar gain ratio							

Considering the data, SPD glazing exhibited the lowest SHGC (0.05), representing the highest performance in restricting solar heat gains. Electrochromic glazing also performed remarkably well, with an SHGC of 0.18, indicating strong potential to significantly reduce cooling demands. PDLC and PC glazing offered moderate performance, providing some level of solar heat control but not to the extent of SPD or EC glazing. Conversely, base-case glazing demonstrated the poorest performance, with a high SHGC (0.819), suggesting excessive heat ingress and higher energy consumption for cooling.

b) U-Value (S-2.2)

The U-value quantifies the rate of heat transfer through glazing via conduction, convection, and radiation. Lower U-values indicate superior insulating properties, directly contributing

to improved occupant thermal comfort and reduced energy use [134, 135]. The U-value results for the studied smart glazing alternatives are summarized in Table 45.

The results clearly indicate that Gasochromic (GC) glazing substantially outperformed other glazing types in terms of insulation, exhibiting a notably low U-value of $2.6 \text{ W/m}^2\cdot\text{K}$. This suggests that GC glazing significantly minimizes heat conduction, thereby positively influencing thermal comfort and energy efficiency. EC glazing also demonstrated moderate insulation capabilities, substantially better than conventional glazing systems. In contrast, the base case and the other alternatives (PDLC, SPD, TC, TT, PC) performed poorly, exhibiting high U-values ranging from approximately 5.5 to $5.9 \text{ W/m}^2\cdot\text{K}$.

c) Predicted Mean Vote (PMV) (S-2.3)

The Predicted Mean Vote (PMV) quantifies occupant thermal sensation on a standardized scale, where values from -0.5 to $+0.5$ indicate comfortable conditions, values below -0.5 are considered cool, and above $+0.5$ are considered warm, according to ASHRAE Standard 55 (2020) and ISO 7730 [209]. Table 46 and Figure 41 illustrate the monthly PMV values and corresponding summer averages for each smart glazing alternative, categorized as cool ($\text{PMV} < -0.5$), comfortable ($-0.5 \leq \text{PMV} \leq +0.5$), and warm ($\text{PMV} > +0.5$).

Results indicate that nearly all smart glazing alternatives consistently maintained PMV values within the comfortable range throughout the simulation year, with only minor deviations. In April, all glazing types exhibited slightly cool conditions, ranging from -0.717 (SPD glazing) to -0.501 (TT glazing), while in October, Thermochromic (TC, $\text{PMV} = 0.509$), Thermotropic (TT, $\text{PMV} = 0.531$), and Gasochromic (GC, $\text{PMV} = 0.507$) glazing systems presented slightly warmer sensations. However, the calculated summer-average PMV values (June, July, and August) for all glazing alternatives consistently

remained within the recommended comfortable range, confirming their suitability for thermal comfort in Riyadh's hot climate. Thus, the standardized summer-average PMV values (June, July, and August) listed in **Table 34** are comfortably within the neutral range.

Table 46: Monthly PMV values and summer averages for smart glazing alternatives

Date	Smart glazing alternatives								Min. PMV	Max. PMV
	Base case	EC	PDLC	SPD	TC	TT	PC	GC		
01/01/24	-0.176	-0.334	-0.379	-0.522	-0.294	-0.258	-0.320	-0.174	-0.522	-0.174
01/02/24	-0.023	-0.218	-0.230	-0.376	-0.146	-0.108	-0.171	-0.041	-0.376	-0.041
01/03/24	0.319	0.110	0.136	-0.001	0.214	0.246	0.190	0.279	-0.001	0.279
01/04/24	-0.434	-0.677	-0.601	-0.717	-0.529	-0.501	-0.551	-0.514	-0.717	-0.501
01/05/24	-0.192	-0.496	-0.340	-0.442	-0.271	-0.249	-0.291	-0.320	-0.496	-0.249
01/06/24	0.259	-0.094	0.105	0.004	0.175	0.198	0.155	0.104	-0.094	0.198
01/07/24	-0.048	-0.391	-0.187	-0.279	-0.122	-0.102	-0.140	-0.207	-0.391	-0.102
01/08/24	-0.012	-0.349	-0.151	-0.246	-0.082	-0.063	-0.102	-0.167	-0.349	-0.063
01/09/24	-0.149	-0.470	-0.302	-0.409	-0.227	-0.205	-0.248	-0.288	-0.470	-0.205
01/10/24	0.588	0.360	0.442	0.338	0.509	0.531	0.489	0.507	0.338	0.531
01/11/24	0.090	-0.069	-0.051	-0.159	0.012	0.035	-0.007	0.051	-0.159	0.051
01/12/24	0.003	-0.175	-0.201	-0.351	-0.115	-0.079	-0.141	-0.001	-0.351	-0.001
Summer avg.	0.067	-0.278	-0.078	-0.174	-0.010	0.011	-0.029	-0.090	-0.278	0.011
		Cold	-0.5 <		ISO 7730 comfortable range			< 0.5	Hot	

Summer avg.: The average PMV values for June, July, and August

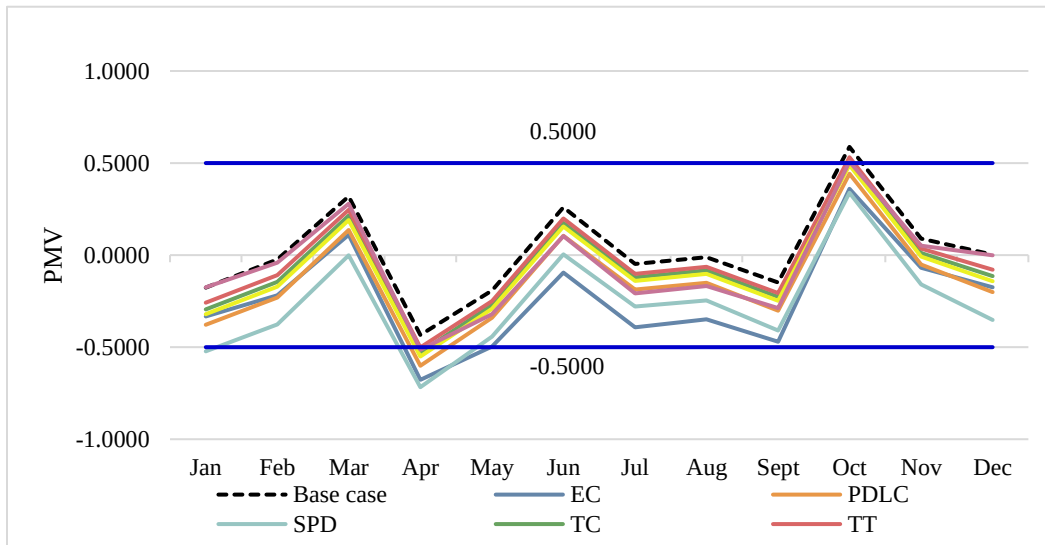


Figure 41: Monthly PMV values in comparison with ISO 7730 recommended comfort range

Moreover, Predicted Mean Vote (PMV) values can be either positive or negative, depending on whether the thermal sensation leans toward warm or cool. However, any deviation from thermal neutrality (PMV = 0) indicates discomfort. In this study, PMV was treated as a cost-type criterion within the MCDM framework. To ensure consistent evaluation, PMV values were converted to their absolute values (i.e., |PMV|), such that greater deviation, regardless of direction, represented poorer thermal comfort. These neutralized values were then used in the **decision matrix**, where lower absolute PMV values were considered more desirable.

d) Predicted Percentage of Dissatisfied (PPD) (S-2.4)

PPD values quantify the estimated percentage of occupants dissatisfied with thermal conditions, ideally kept below 10% per category B (ASHRAE 55 and ISO 7730) [209]. However, Results indicate all glazing alternatives exceeded this threshold (Table 47), except for two months (November and December) suggesting room for improvement.

Thus, the standardized summer-average PPD values (June, July, and August) listed in Table 34 are all slightly above the acceptable threshold (PPD < 10%) and will be utilized for the subsequent decision matrix.

Table 47: Monthly PPD values and summer averages for smart glazing alternatives

Date	Smart glazing alternatives								Min. PPD	Max. PPD
	Base case	EC	PDLC	SPD	TC	TT	PC	GC		
01/01/24	10.6	10.3	11.5	13.9	11.6	10.8	11.2	9.8	9.8	13.9
01/02/24	10.1	9.45	10.7	12.1	10.6	10.0	10.5	9.3	9.3	12.1
01/03/24	11.1	8.69	9.2	9.1	9.8	10.1	9.6	10.2	8.6	10.2
01/04/24	16.4	21.2	19.6	22.8	18.1	17.5	18.5	17.3	17.3	22.8
01/05/24	13.7	18.6	15.2	17.2	14.4	14.1	14.6	15.0	14.1	18.6
01/06/24	13.4	14.51	13.0	13.5	13.0	13.1	13.0	13.0	13.0	14.5
01/07/24	13.6	17.89	14.4	15.5	13.9	13.8	14.0	14.7	13.8	17.8
01/08/24	13.3	17.13	13.9	15.1	13.5	13.4	13.6	14.2	13.4	17.1

Date	Smart glazing alternatives								Min. PPD	Max. PPD
	Base case	EC	PDLC	SPD	TC	TT	PC	GC		
01/09/24	13.5	18.17	14.7	16.6	14.0	13.8	14.1	14.7	13.8	18.1
01/10/24	15.4	10.6	12.2	10.5	13.5	14.0	13.1	13.4	10.5	14.0
01/11/24	9.1	7.6	8.1	8.4	8.4	8.6	8.3	8.2	7.6	8.6
01/12/24	9.6	8.4	9.4	10.8	9.2	9.2	9.2	8.7	8.4	10.8
Summer avg.	13.5	16.5	13.8	14.7	13.5	13.4	13.6	14.0	13.4	16.5
Summer average: The average PMV values for June, July, and August										

e) Annual Window Heat Gain (S-2.5)

Annual window heat gain represents the cumulative amount of solar energy transmitted through glazing over the year, directly affecting indoor thermal conditions and cooling energy demand. Lower values are indicative of superior solar control performance, particularly relevant in hot climates like Riyadh. The simulation results for each smart glazing alternative are summarized in **Table 48** and **Figure 42**.

The results highlight significant differences in solar heat gain performance. Electrochromic glazing displayed outstanding solar heat mitigation capabilities, with the lowest annual heat gain of 8,702.9 kWh. SPD glazing followed closely with 15,941.4 kWh, emphasizing its efficacy in solar control. The base case exhibited the highest heat gain at 973,975.9 kWh, underscoring its inadequacy in thermal performance. Other alternatives like Thermochromic (350,053.2 kWh) and Thermotropic (543,648.8 kWh) presented moderate to high heat gain, highlighting varying degrees of effectiveness.

Thus, the total annual window heat gain values listed in **Table 48** will be utilized for the subsequent decision matrix.

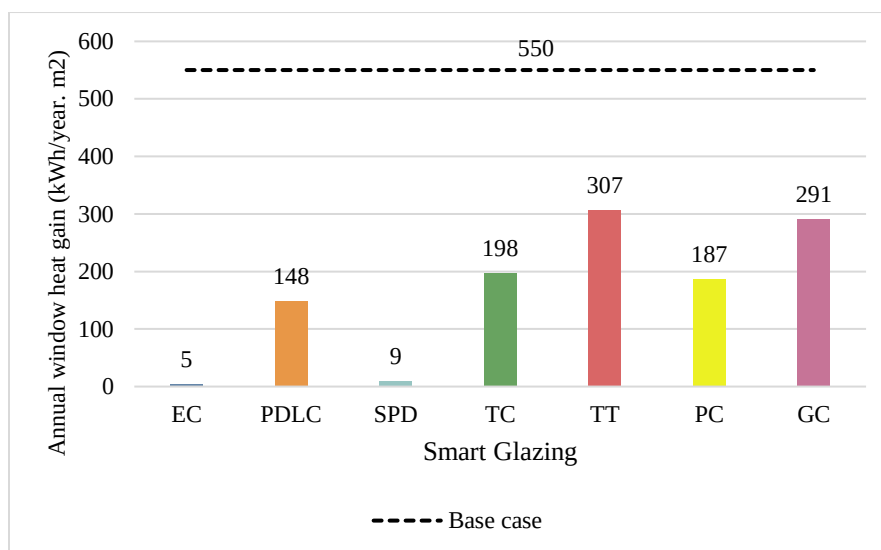


Figure 42: Annual window heat gain (kWh/year. m2)

Table 48: Annual window heat gain (kWh)

Month	Smart glazing alternatives								Min. heat gain	Max. heat gain
	Base case	EC	PDLC	SPD	TC	TT	PC	GC		
Jan	84038	753.3	22844	1390.9	30318	47069	28695	45212.8	753.3	47069
Feb	78561	702.3	21274	1293.5	28201	43850	26728	41759.1	702.3	43850
Mar	84451	752.3	22744	1380.2	30220	46961	28615	44142.1	752.3	46961
Apr	77553	692.3	20863	1262.7	27851	43248	26338	40587.7	692.3	43248
May	79841	713.6	21493	1300.5	28732	44594	27155	41967.0	713.6	44594
Jun	77913	695.6	20924	1264.4	28016	43469	26464	40816.9	695.6	43469
Jul	77848	695.5	20929	1265.3	28005	43458	26460	40858.3	695.5	43458
Aug	77828	695.5	20973	1270.4	27977	43453	26466	40855.4	695.5	43453
Sept	80733	719.5	21701	1314.0	28933	44931	27367	42132.9	719.5	44931
Oct	89826	800.9	24176	1464.8	32146	49998	30458	47185.9	800.9	49998
Nov	79981	716.2	21711	1321.3	28788	44738	27272	42845.2	716.2	44738
Dec	85397	766.0	23220	1413.5	30860	47875	29184	46081.4	766.0	47875
Annual window heat gain (kWh/year)	973975	8702	262857	15941	350053	543648	331204	514444	8702.9	543648

f) Indoor Temperature (S-2.6)

Indoor temperature was assessed using operative temperature, which accounts for both air temperature and mean radiant temperature, offering a more comprehensive representation of thermal comfort. According to ISO 7730, the acceptable operative temperature range for

office buildings in summer is $24.5 \pm 1.5^{\circ}\text{C}$ [136]. Table 49 presents the monthly operative temperature values for each glazing alternative, including average values for the summer months of June, July, and August. The results reveal notable differences among the glazing alternatives. The Base case recorded the highest summer average operative temperature (26.73°C), exceeding the upper limit of the ISO 7730 comfort range, indicating reduced thermal comfort during the hottest period. Conversely, Electrochromic (EC) glazing achieved the lowest average (25.67°C), staying well within the comfort range and reflecting effective solar heat reduction. SPD (25.99°C), GC (26.25°C), and PDLC (26.29°C) also performed relatively well, maintaining indoor conditions near the upper comfort boundary. Thermochromic (TC), Thermotropic (TT), and Photochromic (PC) glazing alternatives showed slightly higher summer averages ($26.44\text{--}26.56^{\circ}\text{C}$)

Table 49: Monthly Indoor operative temperature ($^{\circ}\text{C}$)

Month	Smart glazing alternatives								Min. PPD	Max. PPD
	Base case	EC	PDL C	SPD	TC	TT	PC	GC		
Jan	22.7	22.0	21.8	21.2	22.2	22.3	22.1	22.7	21.2	22.7
Feb	23.6	22.7	22.7	22.0	23.0	23.2	22.9	23.5	22.0	23.5
Mar	24.9	24.0	24.1	23.5	24.4	24.6	24.3	24.7	23.5	24.7
Apr	25.0	24.2	24.5	24.1	24.7	24.8	24.6	24.7	24.1	24.8
May	26.0	25.0	25.5	25.2	25.7	25.8	25.7	25.6	25.0	25.8
Jun	27.3	26.3	26.9	26.6	27.1	27.1	27.0	26.9	26.2	27.1
Jul	26.4	25.4	26.0	25.7	26.2	26.3	26.1	25.9	25.4	26.2
Aug	26.5	25.4	26.0	25.7	26.2	26.3	26.2	26.0	25.4	26.3
Sept	26.1	25.1	25.6	25.3	25.9	25.9	25.8	25.7	25.1	25.9
Oct	26.1	25.1	25.4	25.0	25.7	25.8	25.6	25.7	25.0	25.8
Nov	23.8	23.1	23.2	22.7	23.5	23.6	23.4	23.6	22.7	23.6
Dec	23.3	22.6	22.4	21.8	22.8	23.0	22.7	23.3	21.8	23.3
Summer avg.	26.7	25.7	26.3	26.0	26.5	26.6	26.4	26.3	25.7	26.6
Summer average: The average PMV values for June, July, and August										

g) Light-to-Solar Gain Ratio (LSG) (S-2.6)

The Light-to-Solar Gain Ratio (LSG) is a key indicator used to evaluate the ability of glazing systems to provide daylight while minimizing solar heat gain. It is defined as the

ratio of VLT to the SHGC. A higher LSG indicates a more effective balance between daylighting and solar control. According to the U.S. Department of Energy's Federal Energy Management Program (FEMP), an LSG of **1.25 or greater** qualifies as **green or spectrally selective glazing**, offering both energy efficiency and visual comfort. [217]

The LSG values for the smart glazing alternatives were calculated using VLT and SHGC data provided in Table 35 and are summarized in Table 45. As results indicated (Figure 43, Table 45), PDLC glazing achieved the highest LSG (1.199), indicating the best balance between visible light transmission and solar heat control among all alternatives, though still slightly below the FEMP threshold of 1.25 for spectrally selective glazing. The Base case (1.076), GC (1.038), and SPD (1.000) also provided relatively good LSG values, while EC (0.078) and TC (0.172) performed poorly in this regard, primarily due to their low VLT despite strong solar control.

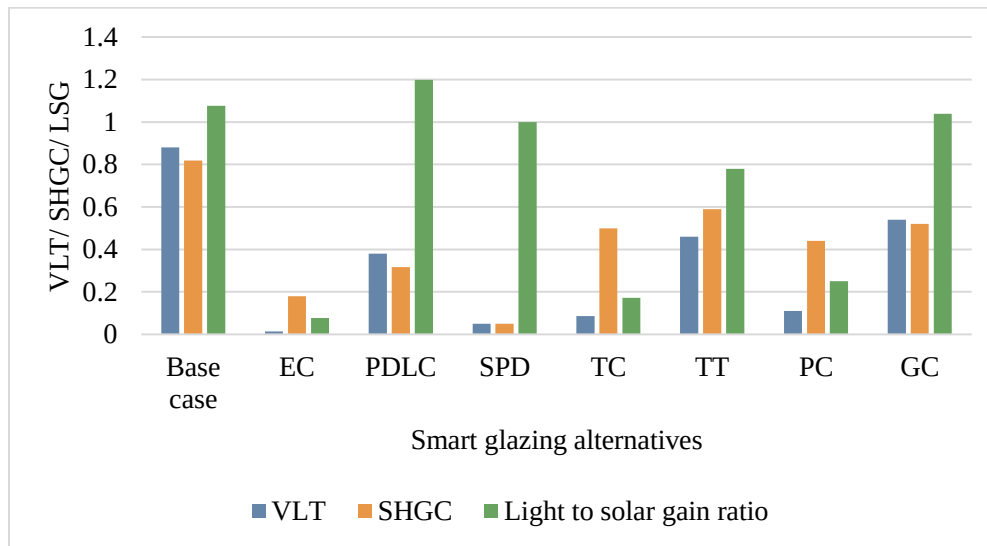


Figure 43: LSG ratio of smart glazing alternatives

4.6.3.3 Acoustic Comfort (Soc-3) Results

This section presents the acoustic comfort performance results for smart glazing alternatives, assessed through the Sound Transmission Class (STC) rating. Acoustic

comfort is evaluated based on the capability of each glazing type to attenuate external noise, as measured by the STC rating. A comprehensive comparative analysis highlights variations in acoustic performance influenced by glazing configuration, thickness, and type.

a) STC (Soc-3.1)

The acoustic comfort performance of smart glazing alternatives was evaluated using the Sound Transmission Class (STC) metric, considering glazing type (monolithic or laminated), configuration, and thickness. The finalized STC values, including references and justifications for their selection, are summarized in Table 50. The results indicated that the laminated glazing alternatives (EC, PDLC, SPD, TT, PC; STC = 35-36) demonstrated significantly higher acoustic insulation than monolithic alternatives (TC, GC; STC = 31). This improved acoustic performance in laminated glazing is attributed primarily to the presence of an interlayer that enhances sound-damping capabilities. The adaptive or dynamic properties of smart glazing technologies did not influence acoustic insulation; rather, performance predominantly depended on glazing thickness and configuration (laminated versus monolithic).

Table 50: STC values for selected smart glazing alternatives

Alternative	ID	Thickness (mm)	Glazing Type	STC value (Selected)	Reference/Justification
Base case	A	6	Monolithic	31	Dominant STC [143-147]
EC	A7	07	Laminated	35	STC [145]
PDLC	A1	08	Laminated	35	STC [145]
SPD	A8	08	Laminated	35	STC [145]
TC	A6	07	Monolithic	32	STC [143]
TT	A9	09	Laminated	36	Dominant STC [143, 145]
PC	A10	08	Laminated	35	STC [145]
GC	A4	06	Monolithic	31	Dominant STC [143-147]

4.6.3.4 Summary of Social Performance

The social sustainability assessment of smart glazing alternatives evaluated occupant-centered performance indicators across three domains: visual comfort, thermal comfort, and acoustic quality. These indicators are essential for ensuring indoor environmental quality, occupant well-being, and long-term usability of non-domestic buildings in hot climates.

The results revealed distinct performance patterns among the alternatives. Gasochromic (GC) and Thermotropic (TT) glazing systems performed most favourably in visual comfort, achieving the highest scores in daylight autonomy (DA), useful daylight illuminance (UDI), and daylight factor (DF). These alternatives provide excellent daylight availability and support visual comfort, though they also exhibited relatively higher glare potential due to elevated visible transmittance (VLT). Electrochromic (EC) and SPD glazing demonstrated exceptional glare reduction, with the lowest daylight glare index (DGI) values, but their limited visible transmittance led to low daylight autonomy and reduced useful daylight ranges. In contrast, PDLC glazing showed a well-balanced profile, performing moderately in daylight access and glare control while achieving the highest light-to-solar gain ratio (LSG), indicating strong overall efficiency in daylight delivery relative to solar heat gain.

Thermal comfort analysis showed that all alternatives-maintained summer average PMV values within ASHRAE and ISO-defined comfort ranges. Electrochromic and SPD glazing also achieved the lowest solar heat gain (SHGC), contributing positively to indoor thermal conditions.

Gasochromic glazing further distinguished itself with the lowest U-value ($2.6 \text{ W/m}^2\cdot\text{K}$), reflecting superior thermal insulation.

Acoustic performance, assessed through Sound Transmission Class (STC) ratings, was satisfactory for all systems. EC, PDLC, and SPD showed the most favourable acoustic insulation ($\text{STC} \geq 35$), while Gasochromic and Thermotropic slightly underperformed in this category.

Table 51 summarizes the most and least favourable alternatives for each social sustainability criterion. The actual evaluated performance values for each sub-criterion, as reported in their respective sections, are used directly as inputs in the final decision matrix for the multi-criteria decision-making (MCDM) framework, enabling a comprehensive sustainability assessment.

Table 51: Comparative Summary of Social Performance Across Smart Glazing Alternatives

Main criteria	Sub-criteria		Most favourable alternative(s)	Least favourable alternative(s)
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	GC, TT	EC
	S-1.3	Daylight Glare Index (DGI)	EC, SPD	GC, TT
	S-1.4	Daylight Autonomy (DA)	GC, TT	EC, SPD
	S-1.5	Daylight Factor (DF)	GC, TT	EC, SPD
	S-1.6	Uniformity of daylight	GC, TT	EC, SPD
	S-1.7	Useful Daylight Illuminance (UDI)	None	All
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	SPD, EC	TT, Base
	S-2.2	U-Value	GC	SPD, PDLC
	S-2.8	Predicted Mean Vote (PMV)	EC, SPD	TT
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	PDLC, PC	EC, SPD
	S-2.10	Annual window heat gain	EC, SPD	Base, TT
	S-2.11	Indoor temperature	PDLC, GC	EC, TC
	S-2.12	Light-to-solar gain ratio (LSG)	EC, PDLC, SPD	TT, GC
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	GC, TT	EC

4.6.4 Economic Performance Results

4.6.4.1 Cost (Ec-1)

Economic performance significantly influences the adoption and selection of smart glazing technologies, particularly given the notable upfront investment involved. This section comprehensively presents the results from the economic assessment conducted to evaluate the financial implications and cost-effectiveness of different smart glazing alternatives compared to conventional clear glazing (6mm). The analysis encompasses the following sub-criteria:

- Initial Cost / Glazing Unit Cost (Ec-1.1)
- Cooling Cost Savings (Ec-1.2)
- Total Energy Cost Savings (Ec-1.3)
- Payback Period (PBP) (Ec-1.4)

Each criterion has been systematically analysed, ensuring transparency and consistency across alternatives.

a) Initial Cost / Glazing Unit Cost (Ec-1.1)

The initial cost of each smart glazing alternative was obtained from manufacturer quotes, supplier websites, and literature as summarized in **Table 52**. Among the smart glazing alternatives, SPD glazing exhibited the highest cost at \$538/m², followed by photochromic (\$269/m²) and electrochromic (\$240/m²) glazing. In contrast, thermochromic (\$172/m²) and gasochromic (\$200/m²) glazing were among the lower-cost options. PDLC glazing (\$229.6/m²) also had a comparable cost, with its primary advantage being privacy control rather than energy efficiency. Overall, passive technologies (TC, TT, and GC) exhibited the

lowest initial costs, whereas actively controlled glazing options (SPD, EC, PDLC) incurred higher investment costs.

Table 52: Initial cost estimates of Smart glazing alternatives

ID	Smart glazing alternatives	Cost per m ² (USD)	Cost estimation source / Reference
A	Base case	100.0	Energy Plus Database
A7	Electrochromic (EC)	240.0	[162]
A1	Polymer Dispersed Liquid Crystal (PDLC)	229.6	[218]
A8	Suspended Particle Device (SPD)	538.0	[219]
A6	Thermochromic (TC)	172.0	[220]
A9	Thermotropic (TT)	^A 200.0	^A Prototype
A10	Photochromic (PC)	^B 269.0	[219]
A4	Gassochromic (GC)	^C 200.0	^C Prototype

Notes:

^A Thermotropic glazing currently lacks direct market prices. It's passive, simpler in design, and similar to thermochromic glazing but slightly less mature.

^B Here the reference [219], referred the Photochromic glazing as smart tint glass with the cost range of \$ 25 to \$ 45 .

^C Gasochromic glazing cost is estimated based on similarity to electrochromic glazing, but with simpler coating processes offset by additional costs for the gas-handling system. [221]

It is essential to acknowledge several key limitations associated with these cost estimations:

- **Market variability:** Smart glazing prices vary significantly based on factors like order quantity, geographic location, customization, and supplier differences, especially for imported products. Thus, actual project-specific costs might differ from the estimates presented in this study.
- **Prototype technologies:** Technologies such as thermotropic and gasochromic glazing are still in the research and development stage. Costs for these technologies have been estimated based on comparable, more commercially mature glazing systems, literature, and projected market entry costs.
- **Additional costs:** The presented initial costs exclude installation, customization, system integration, control equipment, maintenance, and operational expenses (such as

electricity consumption for active systems or gas replenishment for gasochromic glazing).

Therefore, the initial costs presented herein serve primarily as indicative benchmarks for comparative analysis. Decision-makers should carefully consider these limitations and conduct project-specific assessments for accurate financial planning.

b) Cooling Cost Savings (Ec-1.2)

Cooling cost savings are particularly critical for buildings in cooling-dominated climates such as Saudi Arabia. Table 53 summarizes the cooling energy savings and associated annual cost reductions resulting from the application of smart glazing technologies relative to the baseline (clear glazing), using a commercial electricity tariff of \$0.08/kWh (Saudi Electricity Company).

The results indicate that SPD glazing achieved the highest cooling cost savings, reflecting a 13.38% reduction compared to the base case, followed by Electrochromic (EC) glazing (10.40%). In contrast, thermochromic (TC) and thermotropic (TT) glazing exhibited moderate cooling cost savings (4.45% and 3.35% annually, respectively). Gasochromic glazing (GC) demonstrated cooling cost savings of 6.16%, indicating a moderate performance. PDLC glazing, despite its high initial cost, showed reasonable cooling savings (8.44%), but its opaque off-state limits its daylight optimization.

Table 53: Cooling cost savings of smart glazing alternatives

Smart glazing alternatives	Energy consumption for cooling	Energy saving for cooling	Per kWh Cost of Electricity (SEC)	Cooling energy cost savings	
	KWh/yr	KWh/yr	USD/KWh	USD	%
Base case	5068420	---	---	---	---
EC	4541090	527329.2	0.08	42186.34	10.40
PDLC	4640820	427599.9	0.08	34207.99	8.44
SPD	4390353	678066.4	0.08	54245.31	13.38

Smart glazing alternatives	Energy consumption for cooling	Energy saving for cooling	Per kWh Cost of Electricity (SEC)	Cooling energy cost savings	
	KWh/yr	KWh/yr	USD/KWh	USD	%
TC	4842667	225752.8	0.08	18060.22	4.45
TT	4898594	169825.8	0.08	13586.06	3.35
PC	4780974	287445.3	0.08	22995.62	5.67
GC	4756127	312292.9	0.08	24983.43	6.16

c) Total Energy Cost Savings (Ec-1.3)

The total energy savings (including all energy use, not just cooling) and associated annual financial benefits are summarized in Table 54. The energy cost is calculated using the Saudi Electricity Company's rate for commercial buildings (USD 0.08/kWh).

The results highlight that SPD glazing (\$47,288.36 annually, 11.16%) achieved the highest total energy savings, making it the most energy-efficient alternative. Electrochromic glazing (EC) followed closely with \$38,648.53 (9.12%) in total energy savings. PDLC glazing provided moderate total energy savings (\$31,015.81, 7.32%), while gasochromic (GC) and photochromic (PC) glazing achieved \$25,432.13 (6.00%) and \$20,338.99 (4.80%) in total savings, respectively. Thermotropic (TT) glazing exhibited the lowest energy cost savings at \$12,421.35 (2.93%).

Table 54: Total energy cost savings of smart glazing alternatives

Smart glazing alternative	Total energy savings	Per kWh Cost of Electricity (SEC)	Total energy cost savings	
	KWh/yr	USD/KWh	USD	%
EC	483106.6	0.08	38648.53	9.12
PDLC	387697.7	0.08	31015.81	7.32
SPD	591104.5	0.08	47288.36	11.16
TC	193926.5	0.08	15514.12	3.66
TT	155266.8	0.08	12421.35	2.93
PC	254237.5	0.08	20339.00	4.80
GC	317901.6	0.08	25432.13	6.00

d) Payback Period (PBP) (Eco-1.4)

The payback period, indicating the duration required to recover initial investment through energy savings, is detailed in **Table 55**. Electrochromic glazing presents the shortest payback period (10.99 years), making it highly financially viable in the long term. Gasochromic and PDLC also provide favorable paybacks (13.92 and 13.10 years, respectively). Conversely, SPD and thermotropic glazing have longer paybacks (20.14 and 28.51 years), suggesting careful consideration before investment due to higher initial costs and payback periods.

Table 55: Payback period of smart glazing technologies

Smart Glazing alternative	Initial cost		Total energy cost savings	Payback period
	USD per m ²	USD per 1770.4 m ²	USD/year	Year
EC	240	424,896	38,648.53	10.99
PDLC	229.6	406,483.84	31,015.81	13.10
SPD	538	952,475.2	47,288.36	20.14
TC	172	304,508.8	15,514.12	19.63
TT	200	354,080	12,421.35	28.51
PC	269	476,237.6	20,338.99	23.41
GC	200	354,080	25,432.12	13.92
Note:				
Case study glazing area: 1770.4 m ²				

4.6.5 Summary of Economic Performance

The economic assessment of smart glazing alternatives considered initial cost, cooling and total energy cost savings, and payback period to evaluate financial viability. Results highlight clear trade-offs between upfront investment and long-term returns.

Electrochromic (EC) glazing emerged as the most economically favourable option, offering substantial energy cost savings and a moderate initial cost, resulting in the shortest payback period (10.99 years). SPD glazing, while achieving the highest annual savings, required

the greatest investment, leading to a longer payback period of 20.14 years. PDLC and Gasochromic glazing showed balanced economic performance, combining moderate costs and savings with payback periods between 13 and 14 years.

Conversely, Thermotropic, Thermochromic, and Photochromic glazing alternatives demonstrated lower economic sustainability due to smaller energy savings and longer payback periods (19.63 to 28.51 years). These extended payback periods are typical for advanced glazing systems, particularly in early market phases where costs are higher, and energy tariffs are relatively low. However, as technologies mature and market adoption increases, production costs are expected to decrease, potentially improving economic feasibility in the future.

Table 56 provides a comparative overview of economic performance across key indicators. As in the previous sections, the evaluated cost and savings performance values are directly incorporated into the MCDM decision matrix to ensure that economic considerations are objectively represented within the overall sustainability evaluation.

Table 56: Economic sustainability ranking

Smart Glazing Alternative	EC	PDLC	GC	TC	SPD	PC	TT
Payback Period (Years)	10.99	13.1	13.92	19.63	20.14	23.41	28.51
Rank	1	2	3	4	5	6	7

4.6.6 Technical Performance Results

4.6.6.1 Operational Efficiency (T-1)

The technical performance assessment provides a comparative evaluation of seven smart glazing technologies based on their switching time, actuation type, power consumption, durability, and commercial maturity. The extracted data were systematically analyzed and

integrated into a multi-criteria decision matrix, enabling a structured and objective comparison of smart glazing alternatives. The results are summarized in Table 57, which presents the operational performance metrics for Electrochromic (EC), Polymer Dispersed Liquid Crystal (PDLC), Suspended Particle Device (SPD), Thermochromic (TC), Thermotropic (TT), Photochromic (PC), and Gasochromic (GC) glazing systems. This section further analyzes the results under each sub-criterion, highlighting key findings and trade-offs among different technologies.

Table 57: Operational performance of smart glazing alternatives

Operational performance sub-criteria	Smart glazing alternatives						
	EC	PDLC	SPD	TC	TT	PC	GC
Switching time (For full transition)	5–12 min [36]	40ms [36]	1–3 s [36]	20–30 min [222]	8–10 min [223]	10 minutes [223]	20–60 s [30]
Actuation	Active (Electrical, 0–10 V DC) [36, 41]	Active (Electrical, 50–100 V AC) [2, 36]	Active (Electrical, 110 V AC) [36, 41]	Passive (Heat/temperature-responsive)	Passive (Temperature-responsive)	Passive (UV/visible light-responsive)	Active (Gas injection, H ₂ /O ₂) [224]
Operational energy use/power requirement for state transition	2.5 W/m ² (Electrical; power needed only during switching—no continuous energy requirement) [36]	5 W/m ² (Electrical; continuous power required to maintain transparent state) [36]	5 W/m ² (Electrical; continuous power required to maintain desired tint state) [36]	0 W/m ² (Passive, no electrical input required)	0 W/m ² (Passive, no electrical input required)	0 W/m ² (Passive, no electrical input required)	0.1–1 W/m ² (Electrical; minimal continuous power required for gas-handling mechanism) [224]
Durability	50 year [36]	10 year [36]	20 year [36]	^C 25 years [222]	^A 20 years [45]	^D 13.6 years [225]	^B 30 years

^A The estimated durability of thermotropic glazing is assumed to be 20 years based on industry standards for similar glazing technologies. Moreover, Polymer-based layers can cycle reversibly many times around the critical temp with minimal degradation [45].

^B Tungsten-oxide coating similar to EC (expected to have comparable durability to EC ≥20 years); system reliability depends on gas-seal and pump longevity (still under evaluation in trials)

^C No electronics to fail; lab tests on thermochromic interlayers show 20–30 year lifespan. Typically sold with 10-year warranties.[222]

^D The photochromic films demonstrated excellent cyclic stability and durability, showing no aging effects on the glass panes after UV exposure and thermal cycling equivalent to 13.6 years [225].

a) Switching Time/Transition Speed (T-1.1)

The switching time, or transition speed, of smart glazing plays a critical role in ensuring rapid adaptability to changing daylight conditions. The results indicate that PDLC exhibited the fastest switching time, transitioning within 40 milliseconds, followed by SPD, which took between 1 to 3 seconds. Electrochromic glazing, in contrast, required 5 to 12 minutes to complete its transition. The passive systems, including thermochromic, thermotropic, and photochromic glazing, had significantly slower transition speeds, ranging between 8 to 30 minutes. Their reliance on external environmental factors, such as temperature and solar radiation, limits their adaptability in rapidly fluctuating lighting conditions. Gasochromic holds exhibited very little switching time between 20 to 60 seconds.

To ensure consistency in data integration for the decision matrix, the maximum value within the given range for each glazing type was considered, with all values standardized to minutes. The processed values are presented in Table 59 facilitating an objective comparison of switching times across all glazing alternatives. This approach ensures that the decision-making model accounts for the worst-case transition speed scenario, which is crucial for assessing glazing performance in real-world applications.

b) Actuation (T-1.3)

The actuation type of smart glazing refers to the mechanism by which the glazing transitions between optical states, determining whether it requires an external power source (active) or functions autonomously based on environmental triggers (passive). The classification of smart glazing into active and passive systems is essential for evaluating energy dependence and control flexibility. The results indicate that electrochromic, PDLC,

and SPD glazing technologies operate as active systems, requiring electrical input to initiate state transitions. Among these, electrochromic glazing requires a DC voltage of 0–10 V for activation, whereas PDLC and SPD operate at higher voltage levels, typically requiring 50–100 V AC and 110 V AC, respectively.

Conversely, thermochromic, thermotropic, and photochromic glazing function as passive systems, meaning they respond automatically to external environmental factors such as temperature or solar radiation without the need for an external power supply. Thermochromic and thermotropic glazing react to temperature variations, while photochromic glazing adjusts its optical properties based on UV or visible light exposure. These passive technologies offer significant energy-saving potential but limit their effectiveness in buildings where real-time daylight modulation is required. Gasochromic glazing classified as an active technology due to its requirement for a small amount of electrical power to inject gases for state transition.

Although actuation type is relevant for system classification, it is categorical variable and not directly quantifiable and therefore excluded from the decision matrix. Instead, its implications are captured through related, measurable criteria such as energy requirement and switching speed.

c) Energy/ Power Requirement for Glazing State (T-1.4)

The operational energy requirement of smart glazing measures the power consumption needed to initiate or maintain different optical states, directly influencing the overall energy efficiency of the system. The findings reveal significant variations in power consumption among different smart glazing technologies, with active systems requiring external power input and passive systems operating without energy consumption.

Results indicated that among active glazing systems, electrochromic glazing was found to be the most energy-efficient, consuming only 2.5 W/m². This power is required only during the switching process, after which the glazing maintains its state without further energy input. This characteristic makes electrochromic glazing a highly efficient choice among active technologies. In contrast, PDLC and SPD require continuous power input to sustain their optical state, consuming approximately 5 W/m². Gasochromic glazing, while classified as an active system, demonstrated very low energy consumption, requiring only 0.1–1 W/m² for gas-handling mechanisms.

On the other hand, passive systems, including thermochromic, thermotropic, and photochromic glazing, require no power input since they self-regulate based on external climatic conditions.

Passive systems (TC, TT, PC) required no external energy input and were therefore assigned a standardized value of 0 W/m² in the decision matrix. For active systems, the maximum power consumption within the reported operational range was used. This conservative approach ensures that the evaluation captures the worst-case energy demand, which is particularly important in hot climatic regions where smart glazing may remain in active states for extended periods. Using the upper bound provides a consistent and risk-averse basis for comparison across technologies, avoiding underestimation of operational energy requirements in real-world conditions. The standardized values are shown in **Table 59**.

d) Durability (T-1.5)

Durability is a key determinant of a smart glazing system's long-term viability and maintenance requirements. The results (Table 57) indicate that electrochromic glazing had

the longest expected lifespan, with a durability of up to 50 years. SPD demonstrated a lifespan of approximately 20 years, whereas PDLC had the shortest lifespan of 10 years. Thermochromic and gasochromic glazing had an estimated lifespan of 20–30 years, depending on environmental exposure and material stability. The findings suggest that electrochromic glazing offers the best long-term performance, reducing the need for frequent replacements and maintenance, which is a key factor in ensuring the sustainability of building materials.

e) Commercial Maturity Level (T-1.7)

Commercial maturity evaluates the extent to which technology has transitioned from research and development to real-world adoption, including factors such as market availability, project adoption, cost competitiveness, and performance validation. The results, presented in Table 58, highlight significant variations in the commercial readiness of different smart glazing alternatives. Electrochromic (EC) glazing emerged as the most commercially mature technology, achieving the highest score of 23. With full commercialization, strong market presence, and frequent adoption in large-scale projects, EC glazing is widely available and validated. PDLC (21) and SPD (19) follow closely, benefiting from high adoption rates and market availability.

Thermochromic (17) and photochromic (14) glazing exhibit moderate commercial maturity, with some market presence but limited real-world adoption and validation. At the lowest end, thermotropic (7) and gasochromic (8) glazing remain in the R&D phase, with minimal to no market presence and real-world applications.

Table 58: Commercial maturity assessment results

Assessment criteria	Smart glazing alternatives						
	<i>EC</i>	<i>PDL</i> <i>C</i>	<i>SPD</i>	<i>TC</i>	<i>TT</i>	<i>PC</i>	<i>GC</i>
TRL (1–5)	5	4	4	4	3	4	3
Market Presence	5	4	4	3	1	2	1
Adoption in Projects	5	4	3	3	1	2	1
Cost Competitiveness	3	5	4	4	1	4	1
Performance	5	4	4	3	1	2	2
Validation	5	4	4	3	1	2	2
Overall Score	23	21	19	17	7	14	8

4.6.7 Summary of Technical Performance

The technical performance assessment evaluated smart glazing alternatives based on switching time, operational energy requirement, durability, and commercial maturity. These indicators reflect the practicality, responsiveness, and technological maturity of each system in building applications.

PDLC and SPD glazing showed the fastest switching capabilities, while passive technologies like Thermochromic (TC) and Thermotropic (TT) exhibited slower response times. Passive systems required no operational energy input, whereas PDLC and SPD consumed the most due to their need for continuous power. Electrochromic (EC) glazing offered the highest durability (50 years) and ranked highest in commercial maturity, followed by PDLC and SPD. Gasochromic (GC) and Thermotropic (TT) remained in early-stage development with lower maturity scores. **Error! Not a valid bookmark self-reference.** summarizes the standardized comparative performance values across technical indicators for the inclusion in the decision matrix. For sub-criteria reported as performance ranges (e.g., switching time and power consumption), the maximum values were used to

ensure a conservative and risk-aware comparison, reflecting worst-case operational scenarios relevant to real-world conditions.

Table 59: Technical performance standardized data for decision matrix

Operational performance sub-criteria	ID	Unit	Smart glazing alternatives						
			EC	PDLC	SPD	TC	TT	PC	GC
Switching time/Transition speed (For full transition)	T-1.1	min	12	0.00067	0.05	30	10	10	1
Energy power requirement for glazing state	T-1.4	W/m ²	2.5	5	5	0	0	0	1
Durability	T-1.5	Years	50	10	20	25	20	13.6	30
Commercial maturity	T-1.7	Points	23	21	19	17	7	14	8

4.7 Multi-Criteria Decision Model Results

The final stage of this study involved applying a multi-criteria decision-making (MCDM) framework to rank the smart glazing alternatives based on their sustainability performance. The inputs for this evaluation were derived directly from the simulation-based performance results and literature review presented in the preceding section. These quantified values across energy, visual, thermal, acoustic, cost, and operational criteria were compiled to form the final decision matrix, which serves as the basis for subsequent normalization, weighting, and ranking procedures.

4.7.1 Final Decision Matrix

The final decision matrix, presented in **Table 60**, consolidates the performance data of the seven smart glazing alternatives across the validated sustainability sub-criteria. Each alternative (EC, PDLC, SPD, TC, TT, PC, and GC) was assessed using a combination of simulation-based and literature-sourced performance values. This matrix formed the foundational input for the multi-criteria decision-making (MCDM) process conducted in this study.

Table 60: Final decision matrix for smart glazing alternatives

Main criteria	Sub-criteria		Smart glazing alternatives							
			Unit	EC	PDLC	SPD	TC	TT	PC	GC
				A7	A1	A8	A6	A9	A10	A4
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	kWh/year	236497.9	249236	283632.8	230462.1	224037.5	236193.9	203964.6
	En-1.2	Energy consumption for cooling	kWh/year	4541090	4640820	4390353	4842667	4898594	4780974	4756127
	En-1.3	Energy consumption for artificial lighting	kWh/year	38148.0	21089.5	33752.5	31787.5	20944.8	27437.3	20850.1
	En-1.4	Total energy consumption (HVAC, lighting)	kWh/year	4815736	4911145	4707738	5104916	5143576	5044606	4980941
	En-1.5	Total energy savings	kWh/year	483106.6	387697.7	591104.5	193926.5	155266.8	254237.5	317901.6
	En-1.8	CO ₂ mitigation	kg CO ₂ /year	244403.6	196136.3	299039.8	98107.43	78549.49	128618.7	160826.4
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	Ratio	0.014	0.38	0.05	0.086	0.46	0.11	0.54
	S-1.3	Daylight Glare Index (DGI)	Index	2.88	12.48	7.01	8.22	12.92	9.37	13.23
	S-1.4	Daylight Autonomy (DA)	%	1.42	43.41	1.26	3.69	48.68	7.93	52.77
	S-1.5	Daylight Factor (DF)	%	0.069	2.9	0.2	0.5	3.7	0.7	4.4
	S-1.6	Uniformity of daylight	Ratio	0.00035	0.00075	0.00037	0.00030	0.00039	0.00022	0.00022
	S-1.7	Useful Daylight Illuminance (UDI)	%	6.10	66.2	13.3	29.6	68.3	37.2	69.9
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	Ratio	0.18	0.317	0.05	0.499	0.59	0.44	0.52
	S-2.2	U-Value	W/m ² K	3.523	5.646	5.9	5.7	5.74	5.81	2.6
	S-2.8	Predicted Mean Vote (PMV)	Index	0.278	0.077	0.173	0.009	0.011	0.028	0.090

Main criteria	Sub-criteria		Smart glazing alternatives							
			Unit	EC	PDLC	SPD	TC	TT	PC	GC
				A7	A1	A8	A6	A9	A10	A4
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	%	16.5	13.8	14.7	13.5	13.4	13.5	14.0
	S-2.10	Annual window heat gain	kWh/year	8702.9	262857.8	15941.4	350053.2	543648.8	331204.7	514444.6
	S-2.11	Indoor temperature	oC	25.67	26.28	25.99	26.49	26.55	26.43	26.25
	S-2.12	Light-to-solar gain ratio (LSG)	Ratio	0.077	1.198	1	0.172	0.779	0.250	1.038
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	Rating	35	35	35	32	36	35	31
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	USD	240	229.6	538	172	200	269	200
	Ec-1.3	Total energy cost savings	USD/year	38648.5	31015.8	47288.3	15514.1	12421.3	20339	25432.1
	Ec-1.4	Payback Period (PBP)	years	10.99	13.10	20.14	19.62	28.50	23.41	13.92
	Ec-1.5	Cooling cost saving	USD/year	42186.3	34207.9	54245.3	18060.2	13586.0	22995.6	24983.4
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	min	12	0.00067	0.05	30	10	10	1
	T-1.4	Energy power requirement for glazing state	W/m2	2.5	5	5	0	0	0	1
	T-1.5	Durability	years	50	10	20	25	20	13.6	30
	T-1.7	Commercial maturity level	Points	23	21	19	17	7	14	8

4.7.2 Criteria Classification

Following the formulation of the final decision matrix presented in Section 4.7.1, it was necessary to classify each sub-criterion based on its performance directionality. This classification ensures that the subsequent normalization step accurately reflects whether higher or lower values represent better performance in the context of hot-climate, non-domestic buildings.

In the MCDM framework adopted in this study, all sub-criteria were assigned as either benefit-type or cost-type:

- **Benefit criteria** are those for which higher values are desirable, indicating improved sustainability performance, such as increased daylight availability, greater energy savings, enhanced thermal or acoustic comfort, or superior long-term durability.
- **Cost criteria** are those for which lower values are desirable, as higher values imply increased energy demand, discomfort, or financial burden—undesirable traits in sustainability evaluation.

Table 61 presents the complete classification of each sub-criterion along with a context-specific justification for its classification. This classification was informed by a synthesis of sustainability literature, building performance research, and contextual priorities specific to non-domestic buildings in hot climatic regions.

Table 61: Classification of sub-criteria as cost or benefit

Main criteria	Sub-criteria		Classification	Justification (<i>Specific to Hot-Climate, Non-Domestic Context</i>)
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	Cost	Not significant in hot climates, but any consumption is a cost.
	En-1.2	Energy consumption for cooling	Cost	Critical in hot climates; higher cooling demand increases operational burden.
	En-1.3	Energy consumption for artificial lighting	Cost	More lighting usage increases electricity demand, which is undesirable.

Main criteria	Sub-criteria		Classification	Justification (Specific to Hot-Climates, Non-Domestic Context)
	En-1.4	Total energy consumption (HVAC, lighting)	Cost	Summarizes major energy loads; lower consumption is preferred.
	En-1.5	Total energy savings	Benefit	Indicates performance improvement; higher savings reflect better energy efficiency.
	En-1.8	CO ₂ mitigation	Benefit	Greater mitigation results in better environmental outcomes.
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	Benefit	Even at the most tinted state, higher VLT supports daylighting and reduces lighting energy use. Heat and glare are controlled by separate criteria (SHGC, DGI), avoiding redundancy.
	S-1.3	Daylight Glare Index (DGI)	Cost	Higher DGI indicates visual discomfort; lower values are preferable.
	S-1.4	Daylight Autonomy (DA)	Benefit	Higher DA means daylight sufficiency for longer durations; promotes sustainability.
	S-1.5	Daylight Factor (DF)	Benefit	Higher DF improves daylight access and reduces artificial lighting use. Glare risk is managed separately through DGI
	S-1.6	Uniformity of daylight	Benefit	Better daylight uniformity improves visual comfort and design quality.
	S-1.7	Useful Daylight Illuminance (UDI)	Benefit	Higher UDI indicates effective daylight use suited to occupant needs.
	S-1.7	Useful Daylight Illuminance (UDI)	Benefit	Higher UDI indicates effective daylight use suited to occupant needs.
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	Cost	Higher SHGC allows more solar heat in, increasing cooling loads in hot climates.
	S-2.2	U-Value	Cost	Higher U-value means greater thermal transmission, reducing insulation performance.
	S-2.8	Predicted Mean Vote (PMV)	Cost	Evaluated as absolute deviation from PMV = 0; higher values indicate increased thermal discomfort.
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	Cost	Higher PPD reflects greater occupant discomfort.
	S-2.10	Annual window heat gain	Cost	Increased heat gain raises cooling energy requirements.
	S-2.11	Indoor temperature	Cost	Treated as operative temperature; deviations from comfort range increase HVAC demand and reduce thermal efficiency.
	S-2.12	Light-to-solar gain ratio (LSG)	Benefit	Higher LSG transmits more light with less heat — ideal in hot climates.
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	Benefit	Higher STC improves noise insulation — important in schools, offices, etc.
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	Cost	High initial cost reduces financial feasibility.
	Ec-1.3	Total energy cost savings	Benefit	Directly improves operational cost-efficiency.
	Ec-1.4	Payback Period (PBP)	Cost	Longer payback periods reduce financial attractiveness.
	Ec-1.5	Cooling cost saving	Benefit	Highly relevant in hot climates; more savings improve affordability.
Operational	T-1.1	Switching time/Transition speed	Cost	Longer switching limits adaptive performance and dynamic daylight control.

Main criteria	Sub-criteria		Classification	Justification (Specific to Hot-Climate, Non-Domestic Context)
Efficiency (T-1)	T-1.4	Energy power requirement for glazing state	Cost	Higher power demand reduces energy efficiency of the system.
	T-1.5	Durability	Benefit	Longer lifespan enhances lifecycle sustainability.
	T-1.7	Commercial maturity level	Benefit	Higher maturity indicates lower risk and better feasibility for implementation.

4.7.3 Normalized Decision Matrix

To ensure comparability across sub-criteria with differing units and scales, the decision matrix was normalized using vector normalization, based on the cost–benefit classification.

The resulting normalized decision matrix is presented in Table 62 and served as the input for entropy-based weighting and subsequent TOPSIS evaluation.

Table 62: Normalized decision matrix

Main criteria	Sub-criteria		Classification	Smart glazing alternatives						
				EC	PDLC	SPD	TC	TT	PC	GC
				A7	A1	A8	A6	A9	A10	A4
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	Cost	0.6257	0.6055	0.5511	0.6352	0.6454	0.6262	0.6772
	En-1.2	Energy consumption for cooling	Cost	0.6345	0.6265	0.6466	0.6102	0.6057	0.6152	0.6172
	En-1.3	Energy consumption for artificial lighting	Cost	0.4936	0.7201	0.5520	0.5781	0.7220	0.6358	0.7232
	En-1.4	Total energy consumption (HVAC, lighting)	Cost	0.6331	0.6258	0.6413	0.6110	0.6081	0.6156	0.6205
	En-1.5	Total energy savings	Benefit	0.4929	0.3956	0.6031	0.1979	0.1584	0.2594	0.3244
	En-1.8	CO ₂ mitigation	Benefit	0.4929	0.3956	0.6031	0.1979	0.1584	0.2594	0.3244
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	Benefit	0.0171	0.4643	0.0611	0.1051	0.5621	0.1344	0.6598
	S-1.3	Daylight Glare Index (DGI)	Cost	0.8917	0.5318	0.7371	0.6915	0.5154	0.6484	0.5037
	S-1.4	Daylight Autonomy (DA)	Benefit	0.0168	0.5145	0.0150	0.0437	0.5770	0.0940	0.6254
	S-1.5	Daylight Factor (DF)	Benefit	0.0105	0.4518	0.0446	0.0831	0.5620	0.1095	0.6776
	S-1.6	Uniformity of daylight	Benefit	0.3283	0.6916	0.3456	0.2765	0.3632	0.2078	0.2073
	S-1.7	Useful Daylight Illuminance (UDI)	Benefit	0.0476	0.5168	0.1039	0.2310	0.5335	0.2905	0.5454
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	Cost	0.8354	0.7102	0.9543	0.5438	0.4606	0.5977	0.5246
	S-2.2	U-Value	Cost	0.7410	0.5850	0.5663	0.5810	0.5780	0.5729	0.8089
	S-2.8	Predicted Mean Vote (PMV)	Cost	0.2059	0.7787	0.5045	0.9721	0.9686	0.9174	0.7426

Main criteria	Sub-criteria		Classification	Smart glazing alternatives						
				<i>EC</i>	<i>PDLC</i>	<i>SPD</i>	<i>TC</i>	<i>TT</i>	<i>PC</i>	<i>GC</i>
				<i>A7</i>	<i>A1</i>	<i>A8</i>	<i>A6</i>	<i>A9</i>	<i>A10</i>	<i>A4</i>
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	Cost	0.5628	0.6345	0.6090	0.6423	0.6432	0.6410	0.6281
	S-2.10	Annual window heat gain	Cost	0.9906	0.7169	0.9828	0.6229	0.4144	0.6432	0.4459
	S-2.11	Indoor temperature	Cost	0.6303	0.6214	0.6256	0.6184	0.6175	0.6193	0.6220
	S-2.12	Light-to-solar gain ratio (LSG)	Benefit	0.0379	0.5834	0.4867	0.0839	0.3795	0.1217	0.5054
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	Benefit	0.3870	0.3870	0.3870	0.3538	0.3980	0.3870	0.3427
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	Cost	0.6853	0.6990	0.2946	0.7745	0.7378	0.6473	0.7378
	Ec-1.3	Total energy cost savings	Benefit	0.4929	0.3956	0.6031	0.1979	0.1584	0.2594	0.3244
	Ec-1.4	Payback Period (PBP)	Cost	0.7860	0.7448	0.6079	0.6179	0.4450	0.5441	0.7289
	Ec-1.5	Cooling cost saving	Benefit	0.4853	0.3935	0.6240	0.2078	0.1563	0.2645	0.2874
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	Cost	0.6599	1.0000	0.9986	0.1498	0.7166	0.7166	0.9717
	T-1.4	Energy power requirement for glazing state	Cost	0.6696	0.3392	0.3392	1.0000	1.0000	1.0000	0.8678
	T-1.5	Durability	Benefit	0.6995	0.1399	0.2798	0.3497	0.2798	0.1903	0.4197
	T-1.7	Commercial maturity level	Benefit	0.5237	0.4781	0.4326	0.3871	0.1594	0.3188	0.1821

4.7.4 Entropy Weighting

Shannon entropy method was applied to quantify the objective weights of each sub-criterion based on the degree of variability in its performance values. Criteria exhibiting greater dispersion across alternatives were assigned higher weights, as they contribute more informational value to the decision-making process. In this study, entropy weights were calculated within their respective main criteria categories rather than across all sub-criteria globally. This hierarchical approach was adopted to maintain an internal balance across sustainability dimensions and prevent categories with more sub-criteria from disproportionately influencing the final ranking. Table 63 presents the entropy values (E_j), diversification scores ($1-E_j$), **local entropy weights (w_j)**, and their percentage shares for all sub-criteria.

Table 63: Entropy weights of sub-criteria

Main criteria	Sub-criteria		Entropy value	Diversification degrees	Entropy weight	
			E_j	$1-E_j$	W_j	%
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	0.9991	0.0009	0.0087	0.87%
	En-1.2	Energy consumption for cooling	0.9999	0.0001	0.0012	0.12%
	En-1.3	Energy consumption for artificial lighting	0.9951	0.0049	0.0491	4.91%
	En-1.4	Total energy consumption (HVAC, lighting)	0.9999	0.0001	0.0008	0.08%
	En-1.5	Total energy savings	0.9529	0.0471	0.4701	47.01%
	En-1.8	CO ₂ mitigation	0.9529	0.0471	0.4701	47.01%
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	0.7935	0.2065	0.2324	23.24%
	S-1.3	Daylight Glare Index (DGI)	0.9896	0.0104	0.0117	1.17%
	S-1.4	Daylight Autonomy (DA)	0.7195	0.2805	0.3157	31.57%
	S-1.5	Daylight Factor (DF)	0.7595	0.2405	0.2706	27.06%
	S-1.6	Uniformity of daylight	0.9562	0.0438	0.0493	4.93%
	S-1.7	Useful Daylight Illuminance (UDI)	0.8932	0.1068	0.1202	12.02%
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	0.9841	0.0159	0.0717	7.17%
	S-2.2	U-Value	0.9949	0.0051	0.0231	2.31%
	S-2.8	Predicted Mean Vote (PMV)	0.9598	0.0402	0.1809	18.09%
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	0.9995	0.0005	0.0022	0.22%
	S-2.10	Annual window heat gain	0.9753	0.0247	0.1112	11.12%
	S-2.11	Indoor temperature	1.0000	0.0000	0.0001	0.01%
	S-2.12	Light-to-solar gain ratio (LSG)	0.8643	0.1357	0.6108	61.08%
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	0.9993	0.0007	1.0000	100.00 %
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	0.9834	0.0166	0.1368	13.68%
	Ec-1.3	Total energy cost savings	0.9529	0.0471	0.3890	38.90%
	Ec-1.4	Payback Period (PBP)	0.9918	0.0082	0.0679	6.79%

Main criteria	Sub-criteria		Entropy value	Diversification degrees	Entropy weight	
			E_j	$1-E_j$	w_j	%
	Ec-1.5	Cooling cost saving	0.9508	0.0492	0.4062	40.62%
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	0.9536	0.0464	0.2494	24.94%
	T-1.4	Energy power requirement for glazing state	0.9596	0.0404	0.2168	21.68%
	T-1.5	Durability	0.9389	0.0611	0.3282	0.33
	T-1.7	Commercial maturity level	0.9618	0.0382	0.2055	0.21

Results highlighted that within the Energy Efficiency category (En-1), 'Total energy savings' and 'CO₂ mitigation' emerged as highly influential criteria, each accounting for approximately 47% of the category's total weight. Conversely, criteria related to 'Energy consumption for cooling' and 'Total energy consumption (HVAC, lighting)' exhibited minimal variability, thus receiving considerably lower weights (0.12% and 0.08%, respectively).

For Visual Comfort and Daylighting Performance (S-1), 'Daylight Autonomy (DA)' and 'Daylight Factor (DF)' contributed significantly, with entropy weights of approximately 31.57% and 27.06%, respectively, reflecting their critical roles in evaluating daylight performance. Conversely, 'Daylight Glare Index (DGI)' demonstrated low variability and thus received a minimal weight (1.17%).

Thermal Comfort (S-2) analysis highlighted 'Light-to-Solar Gain Ratio (LSG)' as the dominant criterion, accounting for approximately 61% of the weight within this category, underscoring its significance in balancing daylight benefits against thermal loads. 'Predicted Mean Vote (PMV)' also carried substantial importance (18.09%), while 'Indoor

temperature' and 'Predicted Percentage of Dissatisfied (PPD)' received negligible weights due to minimal variability.

In the Acoustic Comfort category (S-3), only 'Sound Transmission Class (STC)' was evaluated, receiving the full weight (100%) within its category, emphasizing its critical role in assessing acoustic performance.

Within the Economic dimension (Ec-1), criteria related to cost efficiency, such as 'Cooling cost saving' (40.62%) and 'Total energy cost savings' (38.90%), emerged as significant contributors. 'Payback Period (PBP)' demonstrated lower variability and thus a smaller influence (6.79%).

Lastly, Operational Efficiency (T-1) saw relatively balanced entropy weights, with 'Durability' receiving the highest weight (approximately 33%), followed by 'Switching time/Transition speed' (24.94%), 'Energy power requirement for glazing state' (21.68%), and 'Commercial maturity level' (20.55%), indicating balanced variability across operational criteria.

Overall, the entropy weighting analysis for sub-criteria clearly highlights which criteria provide the most discriminative and informative power in the sustainability assessment framework, thereby supporting informed decision-making regarding sustainable smart glazing alternatives.

4.7.5 Subjective Weighting

The subjective weights of the main criteria were derived through a structured Likert-scale survey, in which experts rated the importance of each sub-criterion on a scale of 1 to 5. The

arithmetic mean of each sub-criterion score was calculated, and the total mean for each main criterion was determined by summing the mean scores of all its associated sub-criteria. These totals were then normalized to produce the final subjective weights.

Table 64 presents the results, including the average scores for sub-criteria, total mean per main criterion, and normalized weights. Thermal Comfort received the highest weight (0.2454), followed by Energy Efficiency (0.2241) and Visual Comfort and Daylighting (0.2168). Operational Efficiency and Cost received moderate weights, while Acoustic Comfort was considered least important (0.0310) by the respondents.

These subjective weights were used in conjunction with entropy weights to generate global weights for the final evaluation.

Table 64: Subjective weights of main criteria

Main criteria	Sub-criteria		Mean for sub criteria (From responses)	Total mean for main criteria	Weight for main criteria
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	4.05	26.273	0.2241
	En-1.2	Energy consumption for cooling	4.82		
	En-1.3	Energy consumption for artificial lighting	4.14		
	En-1.4	Total energy consumption (HVAC, lighting)	4.55		
	En-1.5	Total energy savings	4.68		
	En-1.8	CO ₂ mitigation	4.05		
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	4.27	25.409	0.2168
	S-1.3	Daylight Glare Index (DGI)	4.27		
	S-1.4	Daylight Autonomy (DA)	4.45		
	S-1.5	Daylight Factor (DF)	4.23		
	S-1.6	Uniformity of daylight	3.91		
	S-1.7	Useful Daylight Illuminance (UDI)	4.27		
Thermal	S-2.1	Solar Heat Gain Coefficient (SHGC)	4.50	28.773	0.2454

Main criteria	Sub-criteria		Mean for sub criteria (From responses)	Total mean for main criteria	Weight for main criteria
	S-2.2	U-Value	4.41		
	S-2.8	Predicted Mean Vote (PMV)	3.73		
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	3.73		
	S-2.10	Annual window heat gain	4.00		
	S-2.11	Indoor temperature	4.27		
	S-2.12	Light-to-solar gain ratio (LSG)	4.14		
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	3.64	3.636	0.0310
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	4.55	17.227	0.1470
	Ec-1.3	Total energy cost savings	4.50		
	Ec-1.4	Payback Period (PBP)	3.86		
	Ec-1.5	Cooling cost saving	4.32		
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	4.23	15.909	0.1357
	T-1.4	Energy power requirement for glazing state	2.95		
	T-1.5	Durability	4.55		
	T-1.7	Commercial maturity level	4.18		
Total mean of main criteria				117.23	

4.7.6 Global Weights

The calculation of global weights (multiplying the entropy weight of each sub-criterion by the subjective weight of its corresponding main criterion), as illustrated in *Table 65*, integrates subjective expert preferences with objective entropy-derived weights, ensuring that each sub-criterion's overall contribution accurately reflects both measured variability and perceived importance. This combined weighting approach balances the inherent subjectivity of expert judgment with objectively quantified data variability, thus enhancing the robustness and comprehensiveness of the final sustainability assessment. These global weights were subsequently utilized to generate the weighted decision matrix for TOPSIS analysis.

Table 65: Global weights for sub-criteria

Main criteria	Sub-criteria		Sub-criteria weight (Entropy)	Weight for main criteria	Global weights
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	0.0087	0.2241	0.0021
	En-1.2	Energy consumption for cooling	0.0012		0.0003
	En-1.3	Energy consumption for artificial lighting	0.0491		0.0120
	En-1.4	Total energy consumption (HVAC, lighting)	0.0008		0.0002
	En-1.5	Total energy savings	0.4701		0.1146
	En-1.8	CO ₂ mitigation	0.4701		0.1146
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	0.2324	0.2168	0.0504
	S-1.3	Daylight Glare Index (DGI)	0.0117		0.0025
	S-1.4	Daylight Autonomy (DA)	0.3157		0.0684
	S-1.5	Daylight Factor (DF)	0.2706		0.0587
	S-1.6	Uniformity of daylight	0.0493		0.0107
	S-1.7	Useful Daylight Illuminance (UDI)	0.1202		0.0260
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	0.0717	0.2454	0.0176
	S-2.2	U-Value	0.0231		0.0057
	S-2.8	Predicted Mean Vote (PMV)	0.1809		0.0444
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	0.0022		0.0005
	S-2.10	Annual window heat gain	0.1112		0.0273
	S-2.11	Indoor temperature	0.0001		0.0000
	S-2.12	Light-to-solar gain ratio (LSG)	0.6108		0.1499
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	1.0000	0.0310	0.0310
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	0.1368	0.1470	0.0201
	Ec-1.3	Total energy cost savings	0.3890		0.0572
	Ec-1.4	Payback Period (PBP)	0.0679		0.0100
	Ec-1.5	Cooling cost saving	0.4062		0.0597
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	0.2494	0.1357	0.0339
	T-1.4	Energy power requirement for glazing state	0.2168		0.0294
	T-1.5	Durability	0.3282		0.0445
	T-1.7	Commercial maturity level	0.2055		0.0279

4.7.7 Weighted Normalized Decision Matrix

The weighted normalized decision matrix was obtained by multiplying each element of the normalized matrix with its corresponding global weight. This matrix represents the adjusted performance of each smart glazing alternative across all sustainability criteria, integrating both objective performance variability and experts' priorities. Table 66 presents the complete weighted matrix.

Table 66: Weighted normalized decision matrix

Main criteria	Sub-criteria	EC	PDLC	SPD	TC	TT	PC	GC
Energy Efficiency (E-1)	Energy consumption for heating	0.0013	0.0013	0.0012	0.0013	0.0014	0.0013	0.0014
	Energy consumption for cooling	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002	0.0002
	Energy consumption for artificial lighting	0.0059	0.0086	0.0066	0.0069	0.0086	0.0076	0.0087
	Total energy consumption (HVAC, lighting)	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001	0.0001
	Total energy savings	0.0565	0.0453	0.0691	0.0227	0.0181	0.0297	0.0372
	CO ₂ mitigation	0.0565	0.0453	0.0691	0.0227	0.0181	0.0297	0.0372
Visual Comfort and Daylighting Performance (Soc-1)	Visible Light Transmittance (VLT)	0.0009	0.0234	0.0031	0.0053	0.0283	0.0068	0.0332
	Daylight Glare Index (DGI)	0.0023	0.0013	0.0019	0.0018	0.0013	0.0016	0.0013
	Daylight Autonomy (DA)	0.0012	0.0352	0.0010	0.0030	0.0395	0.0064	0.0428
	Daylight Factor (DF)	0.0006	0.0265	0.0026	0.0049	0.0330	0.0064	0.0397
	Uniformity of daylight	0.0035	0.0074	0.0037	0.0030	0.0039	0.0022	0.0022
	Useful Daylight Illuminance (UDI)	0.0012	0.0135	0.0027	0.0060	0.0139	0.0076	0.0142
Thermal Comfort (Sc-2)	Solar Heat Gain Coefficient (SHGC)	0.0147	0.0125	0.0168	0.0096	0.0081	0.0105	0.0092
	U-Value	0.0042	0.0033	0.0032	0.0033	0.0033	0.0032	0.0046
	Predicted Mean Vote (PMV)	0.0091	0.0346	0.0224	0.0432	0.0430	0.0407	0.0330
	Predicted Percentage of Dissatisfied (PPD)	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003	0.0003
	Annual window heat gain	0.0270	0.0196	0.0268	0.0170	0.0113	0.0176	0.0122

Main criteria	Sub-criteria	EC	PDL	SPD	TC	TT	PC	GC
	Indoor temperature	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000	0.0000
	Light-to-solar gain ratio (LSG)	0.0057	0.0875	0.0730	0.0126	0.0569	0.0182	0.0758
Acoustical comfort (Sc-3)	Sound Transmission Class (STC)	0.0120	0.0120	0.0120	0.0110	0.0123	0.0120	0.0106
Cost (Ec-1)	Initial cost /Glazing unit cost	0.0138	0.0141	0.0059	0.0156	0.0148	0.0130	0.0148
	Total energy cost savings	0.0282	0.0226	0.0345	0.0113	0.0091	0.0148	0.0185
	Payback Period (PBP)	0.0078	0.0074	0.0061	0.0062	0.0044	0.0054	0.0073
	Cooling cost saving	0.0290	0.0235	0.0373	0.0124	0.0093	0.0158	0.0172
Operational Efficiency (T-1)	Switching time/Transition speed	0.0223	0.0338	0.0338	0.0051	0.0243	0.0243	0.0329
	Energy power requirement for glazing state	0.0197	0.0100	0.0100	0.0294	0.0294	0.0294	0.0255
	Durability	0.0312	0.0062	0.0125	0.0156	0.0125	0.0085	0.0187
	Commercial maturity level	0.0146	0.0133	0.0121	0.0108	0.0044	0.0089	0.0051

4.7.8 TOPSIS Ranking

The final ranking of the smart glazing alternatives, representing the comprehensive sustainability performance of each alternative, was determined using the TOPSIS method, based on the global weighted normalized decision matrix developed in previous sections. Ideal best (A^+) and ideal worst (A^-) values were identified for each sub-criterion according to whether it was classified as a benefit-type or cost-type. Euclidean distances from both ideal points were then calculated for each alternative, followed by the relative closeness coefficient (C_i^*), as shown in *Table 67* and *Table 68*.

Table 67: Positive ideal solution and negative ideal solution values for each sub-criterion

Main criteria	Sub-criteria		Classification	A^+ (Ideal Best)	A^- (Ideal Worst)
Energy Efficiency (En-1)	En-1.1	Energy consumption for heating	Cost	0.00117	0.00143
	En-1.2	Energy consumption for cooling	Cost	0.00017	0.00019
	En-1.3	Energy consumption for artificial lighting	Cost	0.00591	0.00865
	En-1.4	Total energy consumption (HVAC, lighting)	Cost	0.00012	0.00013
	En-1.5	Total energy savings	Benefit	0.06910	0.01815
	En-1.8	CO ₂ mitigation	Benefit	0.06910	0.01815
Visual Comfort and Daylighting Performance (S-1)	S-1.1	Visible Light Transmittance (VLT)	Benefit	0.03324	0.00086
	S-1.3	Daylight Glare Index (DGI)	Cost	0.00128	0.00187
	S-1.4	Daylight Autonomy (DA)	Benefit	0.04280	0.00103
	S-1.5	Daylight Factor (DF)	Benefit	0.03975	0.00061
	S-1.6	Uniformity of daylight	Benefit	0.00740	0.00222
	S-1.7	Useful Daylight Illuminance (UDI)	Benefit	0.01421	0.00124
Thermal comfort (S-2)	S-2.1	Solar Heat Gain Coefficient (SHGC)	Cost	0.00811	0.01680
	S-2.2	U-Value	Cost	0.00321	0.00459
	S-2.8	Predicted Mean Vote (PMV)	Cost	0.00914	0.04316
	S-2.9	Predicted Percentage of Dissatisfied (PPD)	Cost	0.00031	0.00035
	S-2.10	Annual window heat gain	Cost	0.01132	0.02684
	S-2.11	Indoor temperature	Cost	0.00001	0.00001
	S-2.12	Light-to-solar gain ratio (LSG)	Benefit	0.08746	0.00567
Acoustic comfort (S-3)	S-3.1	Sound Transmission Class (STC)	Benefit	0.01235	0.01063
Cost (Ec-1)	Ec-1.1	Initial cost /Glazing unit cost	Cost	0.00592	0.01557
	Ec-1.3	Total energy cost savings	Benefit	0.03448	0.00906
	Ec-1.4	Payback Period (PBP)	Cost	0.00444	0.00744
	Ec-1.5	Cooling cost saving	Benefit	0.03725	0.00933
Operational Efficiency (T-1)	T-1.1	Switching time/Transition speed	Cost	0.00507	0.03385
	T-1.4	Energy power requirement for glazing state	Cost	0.00998	0.02943
	T-1.5	Durability	Benefit	0.03116	0.00623
	T-1.7	Commercial maturity level	Benefit	0.01460	0.00444

Table 68: Results of TOPSIS

Smart glazing alternatives	Euclidean Distance		Performance score	Sorting
	From Ideal best	From Ideal worst		
	$S_i (+)$	$S_i (-)$		
<i>Electrochromic</i>	0.1112	0.0763	0.40676	5
<i>PDLC</i>	0.0637	0.1081	0.62911	1
<i>SPD</i>	0.0779	0.1103	0.58611	3
<i>Thermochromic</i>	0.1291	0.0358	0.21693	6
<i>Thermotropic</i>	0.1004	0.0808	0.44590	4
<i>Photochromic</i>	0.1197	0.0300	0.20055	7
<i>Gasochromic</i>	0.0692	0.1041	0.60049	2

The TOPSIS ranking results summarized in **Table 68** provide a comprehensive comparative assessment of the evaluated smart glazing alternatives based on their sustainability performance across multiple criteria. Polymer Dispersed Liquid Crystal (PDLC) glazing emerged as the optimal alternative, achieving the highest relative closeness coefficient (C_i^*) value of 0.62911, indicating its superior performance across energy efficiency, visual comfort, thermal comfort, acoustic comfort, cost-effectiveness, and operational efficiency.

Gasochromic glazing followed closely, with a C_i^* value of 0.60049, reflecting a strong overall sustainability performance, particularly in terms of energy savings and operational efficiency. Suspended Particle Device (SPD) glazing ranked third ($C_i^* = 0.58611$), demonstrating robust performance across sustainability dimensions, though slightly lower compared to PDLC and Gasochromic alternatives.

Thermotropic glazing ($C_i^* = 0.44590$) ranked fourth, showcasing moderate sustainability performance, followed by Electrochromic glazing ($C_i^* = 0.40676$) in fifth place. Both

alternatives displayed balanced yet relatively limited performance in key criteria, particularly cost and operational dimensions.

Thermochromic ($C_i^* = 0.21693$) and Photochromic ($C_i^* = 0.20055$) glazing ranked lowest, indicating their less favorable sustainability performance, notably constrained by weaker performance in significant areas such as visual comfort, thermal performance, and economic efficiency.

Overall, the TOPSIS analysis clearly highlights the nuanced trade-offs among sustainability criteria and underscores the importance of integrated assessments for selecting optimal smart glazing technologies for non-domestic buildings in hot climatic conditions.

4.8 Verification of the SG-SAF Framework

The SG-SAF has been rigorously verified through expert input and empirical testing, eliminating the need for additional external validation. *Figure 44* illustrates the multi-stage verification process, which included: (1) expert-driven evaluation of criteria, (2) performance benchmarking via a calibrated building simulation, and (3) the use of robust multi-criteria decision-making (MCDM) techniques. Each component of this verification strategy is discussed critically below, demonstrating that the framework stands on a solid foundation of credibility and aligns with established sustainability assessment practices.

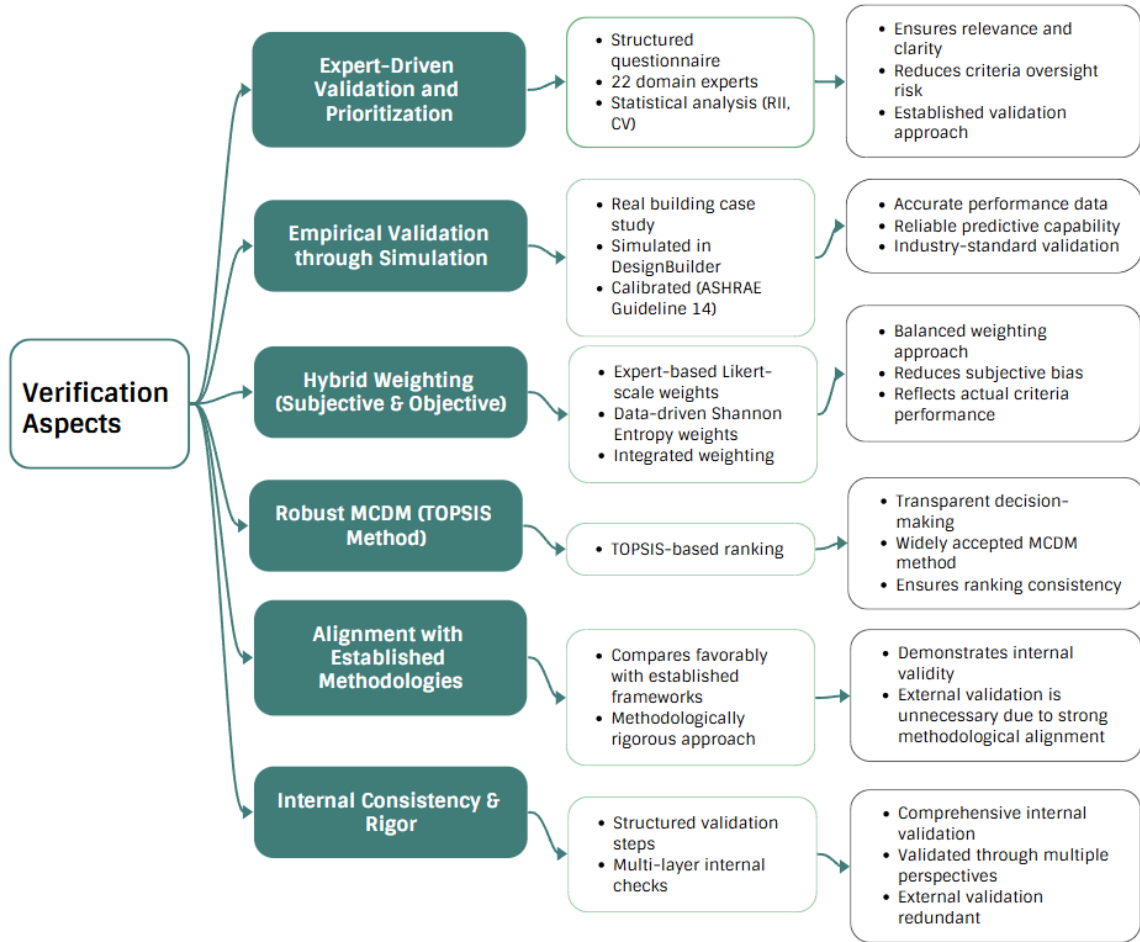


Figure 44: Verification aspects of SG-SAF

4.8.1 Expert-Driven Criteria Validation and Prioritization

A panel of 22 domain experts was engaged through structured questionnaires to validate and refine the sustainability criteria in SG-SAF. This expert elicitation process ensured content validity, confirming that all relevant economic, environmental, and technical factors for smart glazing were represented. Such use of expert panels is a well-established validation approach in sustainability frameworks; for example, Srivastava et al. employed a focus group of experts to validate parameters in a sustainable packaging framework [226]. Likewise, large-scale expert surveys have been used in academia. Ling et al. gathered 188

expert responses to refine a sustainability indicator set [227], underscoring that our targeted expert consultation is in line with peer practices. The experts in SG-SAF's panel, whose profiles spanned industry, academia, and building sustainability domains (Table 69), not only vetted the criteria for relevance and clarity but also prioritized them. Their judgments (captured via Likert-scale ratings) were analysed statistically to derive initial weights for each criterion. This step served as both a validation (ensuring the framework's criteria are appropriate and agreed-upon by practitioners) and a refinement, focusing the framework on the most impactful sustainability factors [226].

Table 69 could visualize the diversity of the expert panel, for instance, a chart of their occupational sectors or years of experience, highlighting the breadth of knowledge underpinning the framework. By integrating diverse expert insights, SG-SAF achieved a high degree of face validity and legitimacy in its construction, reducing the likelihood that any important criterion was overlooked or misinterpreted.

4.8.2 Simulation-Based Performance Verification with Real Data

To verify the framework's performance evaluation stage, SG-SAF was applied to a real building case study using detailed energy simulations. A high-performance building energy model was created in DesignBuilder and calibrated with actual energy consumption data from the building's utility records. This calibration followed industry-standard protocols (ASHRAE Guideline 14), comparing simulated outputs with measured data to ensure accuracy. The importance of such calibration is well documented: *"The accuracy of a building simulation model depends on its validation against actual measured data"*, and a well-calibrated model gives confidence in the model's predictive capability [228].

In this study, key calibration metrics, Normalized Mean Bias Error (NMBE) and Coefficient of Variation of RMSE (CVRMSE), fell within accepted limits, indicating the simulation reliably replicated the building's real energy performance. This means the framework's quantitative assessments (e.g., energy savings from different smart glazing options) are grounded in validated simulation results, not just theoretical estimates. Essentially, the framework was test-run in a practical scenario and showed that its evaluation process can capture real-world performance. This kind of verification with a case study is a strong substitute for external validation: it demonstrates that SG-SAF works as intended under realistic conditions.

Figure 17 summarizes this, showing a branch where the DesignBuilder model is calibrated with actual data before criteria scoring. By ensuring the model's outputs (such as energy, daylight, and comfort metrics for each glazing alternative) are accurate, it can be verified that SG-SAF's performance assessment mechanism is trustworthy. Any recommendations or rankings produced by the framework are thus backed by empirically sound data, reinforcing that external re-testing by third parties would likely yield similar, reliable results.

4.8.3 Robust Weighting Methodology and MCDM Consistency

A critical aspect of SG-SAF's verification lies in its methodological robustness, specifically, the integration of subjective and objective weighting techniques coupled with the TOPSIS decision model. The framework deliberately combines expert judgment weights (derived from Likert-scale ratings) with data-driven weights obtained via Shannon Entropy. This hybrid weighting approach acts as a cross-verification between human

expertise and quantitative evidence. Notably, such a combination is recommended in MCDM literature to enhance reliability: “*The combination of objective weight and subjective weight can reduce the bias of subjective weights and truly reflect the current situation* [229]”.

In this study context, experts’ opinions assign importance to the main criteria (capturing domain priorities), while entropy weights reflect the variability of each sub-criterion’s performance across alternatives (capturing inherent information without human bias). Merging these yields a balanced final weight for each sustainability criterion, mitigating any one expert’s bias or the risk of overlooking subtle data patterns [229]. The use of both expert judgment and entropy for weighting ensures validity.

SG-SAF employs TOPSIS (Technique for Order Preference by Similarity to Ideal Solution), a well-proven multi-criteria ranking technique for the decision-making step. TOPSIS has been widely used in sustainable building decision contexts due to its intuitive logic and effectiveness [97]. It identifies the option closest to the ideal (best) and farthest from the nadir (worst) solution, providing a clear, quantitative ranking of smart glazing alternatives. Extensive prior applications demonstrate the method’s reliability; numerous studies have combined entropy weighting with TOPSIS to solve complex evaluation problems in environmental and construction domains. Moreover, TOPSIS’s simplicity and transparency make it easily accepted by decision-makers [97], which is an indirect validation of its practicality.

The rigorous weighting procedure and the use of a standard MCDM technique mean the SG-SAF’s internal logic is sound and has essentially been verified through multiple lenses.

4.8.4 Summary

In summary, the SG-SAF framework has been thoroughly **verified** through a structured, multi-level approach. This includes expert-driven criteria verification, simulation-based performance benchmarking using ASHRAE-calibrated models, and the application of a transparent, hybrid-weighted MCDM technique. Each component of the framework was built upon established, peer-reviewed methods and cross-checked for internal consistency and methodological soundness.

While external validation through broader case studies or stakeholder testing is recommended as a future step, the current evidence demonstrates that SG-SAF is both **practically credible and academically robust**. By integrating expert insights, reliable simulation outputs, and proven decision-making tools, the framework meets high standards of rigor and is ready for use in research and policy contexts. Therefore, additional external validation is not essential at this stage, as the framework's **internal verification** confirms its reliability, transparency, and applicability for smart glazing assessment in hot-climate, non-domestic buildings.

CHAPTER 5

CONCLUSION

5.1 Conclusions

This research was initiated in response to the increasing demand for sustainable building materials that can effectively balance energy efficiency, occupant comfort, and climate-responsive design, particularly in hot climatic regions. Smart glazing technologies, with their ability to dynamically manage solar heat gain and daylight transmission, offer considerable potential in this context. However, prior to this study, the selection of smart glazing systems remained fragmented, with no unified, performance-driven framework capable of evaluating sustainability holistically across environmental, social, economic, and technical dimensions. To bridge this gap, this study developed the **Sustainability Assessment Framework for Smart Glazing (SG-SAF)**, a robust, practical, expert-informed, and performance-based decision-support tool tailored specifically to **non-domestic buildings in hot climates**. In pursuit of this aim, the study adopted an interdisciplinary methodology integrating systematic literature review, expert validation, calibrated simulation, and multi-criteria decision-making. From a methodological standpoint, **SG-SAF** enables a transparent and structured evaluation and selection framework for smart glazing technologies, merging qualitative expert knowledge with quantitative performance data under a hybrid weighting model, combining Shannon Entropy (objective) and Likert-based expert judgment (subjective). The subsequent application of TOPSIS enabled a structured, transparent, and replicable ranking of seven smart glazing alternatives. The final results of the comprehensive sustainability assessment framework (**SG-SAF**) identified **Polymer Dispersed Liquid Crystal (PDLC) glazing** as

the **most sustainable overall** performer. Its top ranking is attributed to a well-rounded combination of strengths, including excellent visual comfort, effective thermal regulation, notable acoustic insulation, high operational efficiency, and favorable cost-effectiveness. Gasochromic glazing ranked second, driven by its superior energy-saving potential and strong thermal performance, particularly in managing solar heat gain. Suspended Particle Device (SPD) glazing secured the third position, demonstrating consistently strong performance across multiple sustainability dimensions, especially in glare control, daylighting, and environmental impact mitigation.

However, a critical insight that emerged from this study is that achieving **holistic sustainability** (a strong and balanced performance across environmental, social, economic, and technical dimensions) is often challenging in real-world applications. Relying solely on a single, aggregated sustainability score can **oversimplify the inherently multidimensional nature** of material selection. **While the pursuit of holistic sustainability is desirable as a long-term strategic goal, it is not always a practical requirement at the project level.** What is more appropriate is a **contextualized sustainability approach**, one that prioritizes dimensions based on **project-specific goals, climatic conditions, building function, and stakeholder values**. For instance, in hot climates, energy consumption and carbon reduction are paramount; hence, technologies such as SPD or Electrochromic glazing may be more suitable, even if they are not ranked highest overall. This study addresses this by enabling both **comprehensive comparative assessments** and **dimension-specific evaluations for each smart glazing system**, allowing decision-makers to identify the most appropriate glazing solution based on what matters most in their specific scenario.

While the framework itself is the primary contribution of this study, several **key findings and novel insights** emerged along the way that enhance both theoretical understanding and practical implementation:

- A rigorous and context-relevant hierarchy of sustainability criteria was developed through a systematic review of high-quality, domain-specific literature. The criteria were curated based on clarity, relevance, and applicability to smart glazing in hot climate contexts, and were organized under four main sustainability dimensions: environmental, social, economic, and technical. This hierarchy was subsequently validated through input from a panel of qualified experts selected via purposive and snowball sampling methods, encompassing both academic and industry professionals.
- The study introduces two interrelated hierarchies for sustainability assessment. The first was derived from a systematic literature review and critically analyzed for its alignment with sustainability objectives. Sub-criteria were then mapped to smart glazing selection based on the type of relationship (direct or indirect) and the impact of that relationship on performance. The second, more refined hierarchy, was produced through experts' validation of the earlier hierarchy and served as the final structure used within the SG-SAF framework. This two-stage process ensures methodological depth and practical relevance, contributing to a structured pathway for framework development.
- One notable research gap addressed in this thesis is the often-overlooked **acoustic performance** of smart glazing. Although acoustics are not directly influenced by dynamic switching behavior, the study proposed how **Sound Transmission Class (STC)** values can still be quantified and incorporated into sustainability assessments.

This contributes a new understanding to the acoustic evaluation of smart glazing in real-world scenarios.

- To address the often-overlooked challenge of commercial maturity, which can significantly limit the adoption of emerging smart glazing technologies, this study developed a **rubric-based evaluation method**. The rubric provides a structured, transparent, and replicable framework for assessing the commercial readiness of each technology, incorporating key indicators such as Technology Readiness Level (TRL), market presence, adoption in built projects, cost competitiveness, and performance validation. This approach fills a notable methodological gap in existing literature, where the commercial viability of advanced building materials is rarely evaluated in a standardized manner.

Importantly, in the absence of a universally accepted criterion or index for commercial maturity, this study presents a novel, pragmatic method for its assessment. By integrating commercial maturity into the sustainability evaluation, the **SG-SAF** ensures that selected technologies are not only theoretically sustainable but also practically deployable in real-world projects, thereby bridging the gap between innovation potential and implementation feasibility.

- Other than a comprehensive sustainability assessment, each sustainability dimension was assessed independently, concluding with a comparative performance summary of all glazing alternatives. These **dimension-specific evaluations** offer deeper insight beyond aggregated rankings, enabling decision-makers to identify technologies best aligned with specific sustainability priorities. For instance, SPD and Electrochromic (EC) glazing demonstrated superior environmental performance, while Thermochromic glazing stood out in terms of economic feasibility and daylighting

performance. This granularity supports more nuanced, project-specific decision-making.

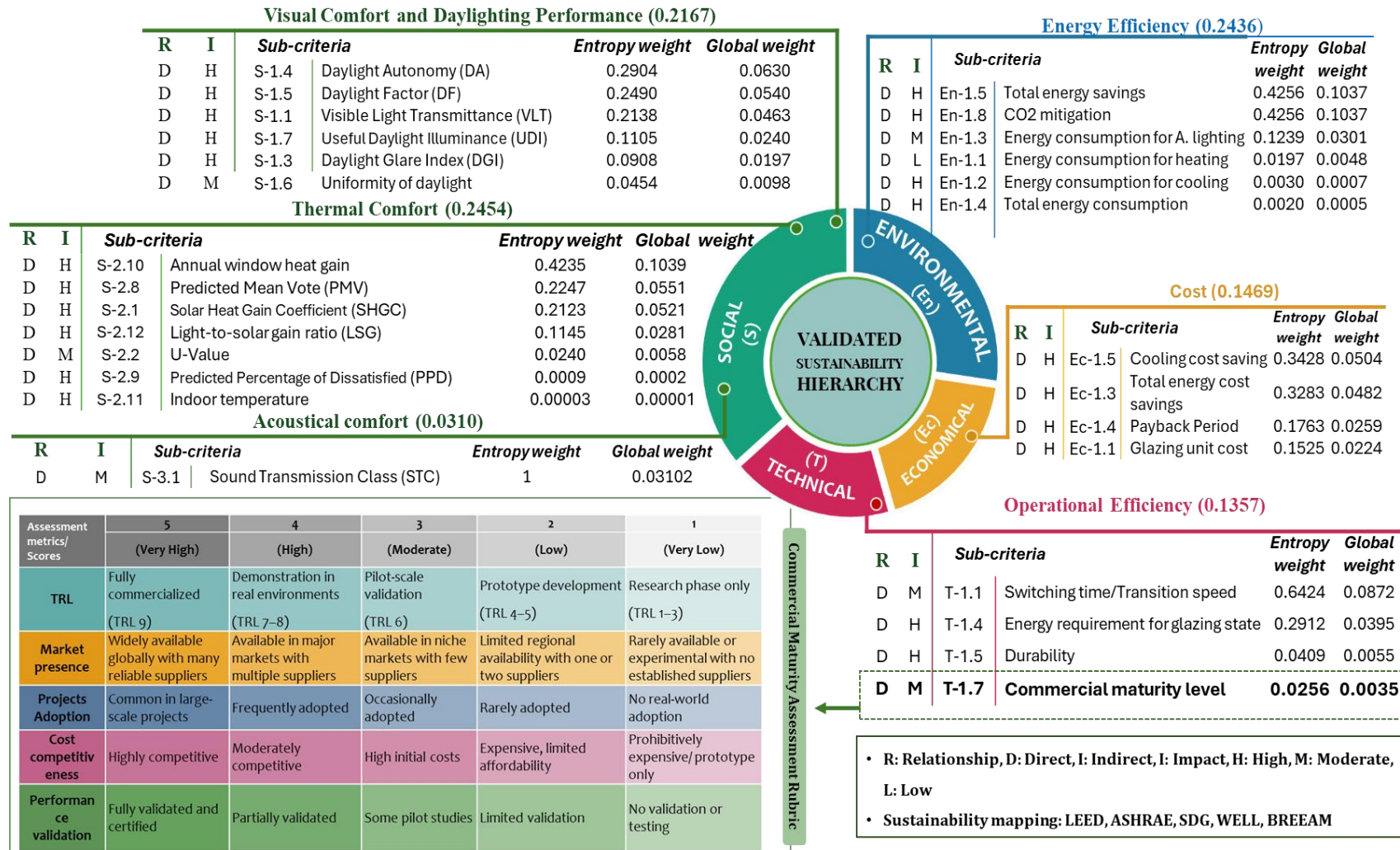
- This study adopted a mixed-method approach that deliberately avoided the **shortcomings of exhaustive pairwise comparisons common in traditional MCDM techniques**. Objective performance data for the sub-criteria were obtained through calibrated simulation models and validated literature, while subjective input was limited to the weighting of main thematic criteria, collected through a streamlined Likert-scale survey. This design ensured methodological efficiency, reduced expert fatigue, and maintained data reliability.
- While **SG-SAF** was specifically developed for smart glazing in non-domestic buildings within hot climates, the framework is inherently modular and scalable. With thoughtful adjustments to input criteria and weighting configurations, it can be adapted for use in other climatic zones, building typologies, or material categories. This adaptability makes the framework suitable not only for current sustainability challenges but also for evolving technological and environmental contexts.

Hence, this research delivers both methodological innovation and practical value. The **SG-SAF** stands as a comprehensive and flexible tool for architects, engineers, sustainability consultants, and developers to evaluate and select smart glazing solutions based on robust, multi-dimensional sustainability criteria. Beyond its academic contributions, the framework directly supports broader sustainability goals, advancing Saudi Vision 2030 and aligning with the United Nations Sustainable Development Goals (SDGs) by promoting low-carbon, high-performance, and resource-efficient building practices.

A key outcome of this study is also visually summarized in the form of a **comprehensive diagram**, presented below. The diagram encapsulates the structure and logic of the SG-

SAF by illustrating the validated sustainability hierarchy. It highlights the relationship (R) and impact (I) of each sub-criterion in selecting smart glazing alternative, along with their corresponding weightings derived through objective data and expert input. In addition, the diagram integrates the rubric-based commercial maturity assessment tool. Together, these visual components offer a clear and structured representation of the framework's decision-making logic, enhancing its usability for both research and practical application in smart glazing selection.

In conclusion, while the **SG-SAF** provides a powerful mechanism for holistic sustainability assessment, its true strength lies in its flexibility. By enabling both comprehensive evaluation and dimension-specific analysis, the framework empowers decision-makers to pursue sustainable glazing strategies that are not only technically sound but also responsive to regional conditions, project-specific goals, and evolving sustainability priorities.



5.2 Future Recommendations

Although the SG-SAF framework provides a rigorous and versatile foundation for sustainability-based decision-making, several avenues for improvement and future exploration have emerged through the research process:

- **Expansion to Other Climates and Building Types**

This study focused specifically on office buildings in hot climates. Future work could adapt and validate the SG-SAF framework for other climatic regions (e.g., cold, temperate, humid) and diverse building typologies such as residential, educational, or healthcare facilities.

- **Integration of Life Cycle and Embodied Impact Assessment**

SG-SAF currently emphasizes operational sustainability. Future iterations should incorporate life cycle assessment (LCA) indicators, such as embodied carbon, material durability, and end-of-life recyclability to provide a more holistic view of glazing sustainability.

- **Inclusion of Broader Stakeholder Perspectives**

The expert validation in this study focused on academic and technical professionals. Future surveys could engage a wider stakeholder base, building occupants, contractors, developers, and policymakers, to capture broader usability, comfort, and implementation concerns.

- **AI-Driven Optimization and Adaptive Learning Models**

Future research could integrate machine learning or genetic algorithms into SG-SAF to automate criteria weighting, identify performance patterns, and suggest optimal solutions under varying project constraints and user preferences.

- **Comparative Evaluation of MCDM Techniques**

This study employed TOPSIS for final decision-making. Future work could compare SG-SAF's performance using other MCDM models (e.g., AHP, VIKOR, PROMETHEE) to assess methodological robustness and sensitivity to different ranking approaches.

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Appendix 1

(Extracted data through Systematic Literature Review)

Category	Indicator	Building type	Climatic region	Climate	Glazing type	Reff / Title
Energy	- Electric energy consumption for cooling - Electric energy consumption for Lighting - Total electric energy consumption (kWh/m²/Year) - Cooling energy savings (%) - Lighting energy savings (%) - Total energy savings (%)	Office	Dhahran, KSA	Hot and humid	EC	[162]
Opto-thermal properties	- VLT - Solar Transmission (%) - SHGC - U-Value (W/m²-K)					
Visual comfort and daylighting	Glare index					
Energy	- Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Total energy consumption (kWh) - Energy consumption for SG operation - Total Energy saving (%)	Office	Riyadh, KSA	Hot and dry	SPD	[116]
Visual comfort and daylighting	- Daylight autonomy (DA_{300lux}) - Useful daylight illuminance (UDI_{100lux-2000lux}) - Daylight glare probability (DGP)					
Opto-thermal properties	- U-value (W/m²K) - SHGC - VLT (%)					
Energy	- Total annual energy consumption (kWh/m²a) - Embodied Energy (MJ/m²a)	Office	Mannheim, Germany	Oceanic climate	EC	[163]
Visual comfort and daylighting	- Useful Daylight Illuminance (UDI) - Daylight glare probability (DGP)					
Thermal comfort	- PMV (Predicted Mean Vote) - PPD (Predicted Percentage of Dissatisfied)					
Life cycle cost	- Glazing unit cost - Glazing transportation fees - Glazing installation cost - Cooling energy cost - Lighting energy cost - Maintenance, repairing, and replacing cost - Disposal cost - Net Present Value (NPV) - Internal Rate of Return (IRR) - Payback Period (PBP) - Total lifecycle cost	Office	New Cairo, Egypt	Arid and dry	EC, Low-E, PV	[24]
Life cycle energy	- Total Life cycle energy (MJ/m²) - Pre-use phase energy (MJ/m²) - Net use-phase energy (MJ/m²) - Net post-use phase energy (MJ/m²)	Office	New Cairo, Egypt	Arid and dry	EC, Low-E, PV	[20]
Life cycle environmental impacts	- Acidification (kg SO₂ eq) - Eutrophication (kg PO₄ P-lim) - Global warming potential (kg CO₂ eq) - Non-renewable energy (MJ primary) - Ozone layer depletion (kg CFC-11 eq) - Terrestrial acid/nutria (kg SO₂ eq)					
Life cycle cost	- Glazing initial cost (\$/m²) - Energy cost (\$) - Glazing Maintenance cost (\$/m²)					

	- Glazing Replacement cost (\$/m²) - Glazing Disposal cost (\$/m²)					
Opto-thermal Properties	- Solar transmittance - Solar reflectance - Solar absorptance - SHGC	Library	Vellore city, India	Tropical savanna climate	PDLC	[164]
Visual comfort and daylighting	- Colour rendering index (CRI) - Correlated Colour temperature (CCT) - Daylight factor (DF)					
Cost	- Cooling energy savings (%) - Payback period (years) - Glazing unit cost (\$/m²) - Cost of energy consumption for SG operation					
Thermal comfort	- Solar heat gains through glazing (MWh) - Solar heat flux through glazing (kWh/m²)					
Energy	CO₂ mitigation (kg-CO₂/m²) (by reducing cooling cost)					
Technical	- Switching time - Memory effect - Fuel/power/Energy requirement for opaque state - Power/Energy requirement for transparent state - Actuation - Durability - Commercial maturity level	Review	--	--	Active smart switchable glazing	[67]
Opto-thermal properties	- SHGC - U-value					
Visual comfort and daylighting	- Useful Daylight Illuminance (UDI) - Glare index - Colour rendering index (CRI) - Correlated Colour temperature (CCT)					
Energy	- Urban heat island (UHI) reduction - CO₂ mitigation					
Cost	Glazing initial cost (\$/m²)					
Opto-thermal properties	- Conductivity (W/mK) - Solar transmittance - Solar reflectance - Visible transmittance - Visible reflectance - Infrared transmittance - Infrared hemispherical emissivity	Office	Different climatic zones of China	--	TC	[165]
Technical	Glazing Thickness					
Energy	Energy Use Intensity (EUI)					
Visual comfort and daylighting	Useful daylight illuminance (UDI)					
Cost	- Glazing initial cost (\$/m²) - Return on investment	Office	California	Hot desert to alpine tundra	EC	[70]
Technical	Design Efficiency/capabilities.					
Thermal comfort	- Annual window heat gain - Internal heat gains - Predicted mean vote (PMV) - Indoor temperature - Light-to-solar gain ratio (LSG)	--	Review study	--	EC TC	[17]
Energy	- Monthly Energy consumption - Annual Energy consumption - Peak day energy consumption - Total energy saving					
Visual comfort and daylighting	- Average annual daylight illuminance - Useful daylight illuminance (UDI) - Daylight glare index (DGI) - Daylight glare probability (DGP) - Illuminance uniformity - Correlated color temperature (CCT) - Color rendering index (CRI)					

Cost	- Glazing initial cost (\$/m²) - Payback period					
Technical	Design of control strategies					
Opto-thermal properties	- U-value - SHGC - VLT	Office	Denver, Colorado	Semi-arid and High desert	GC	
Technical	Tint switching controls					
Visual comfort and daylighting	- Horizontal and vertical illuminance - Illuminance uniformity - Daylight Glare Probability (DGP) - Correlated Colour Temperature (CCT) - Colour Rendering Index (CRI) - Circadian Stimulus Potential (CS) - Equivalent Melanopic Lux (EML) - Direct glare - Brightness - Contrast - View to the outside - Indirect non-visual effect of light – Circadian	Office	Raleigh, North Carolina	Humid subtropical	EC	[32]
Technical	- Switching speed - Glazing color in its tinted states - Light transmittance levels (e.g., 1%, 6%, 40%, 58%.)					
Visual comfort and daylighting	- Daylight Autonomy (DA) - Continuous Daylight Autonomy (DAcon) - Maximum Daylight Autonomy (DAmx) - Useful Daylight Illuminance (UDI) - Daylight Availability (DAv) - Spatial Daylight Autonomy (sDA300/50%) - Annual Sunlight Exposure (ASE1000/250h)					
Energy	- Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Total energy consumption (kWh/yr) - Embodied energy (kWh)	Office	Milan, Italy	Humid subtropical	EC	[166]
Opto-thermal properties	- SHGC - SC - VLT - U-value (W/m²K)					
Cost	- Per unit cost (€) - Energy consumption cost					
Energy	Energy Use Intensity (EUI)	Office	five major climate zones across China		TT	[167]
Visual comfort and daylighting	Spatial Useful Daylight Illuminance (sUDI)					
Thermal comfort	Predicted Mean Vote (PMV)					
Thermal comfort	- Indoor air temperature - Glazing surface temperature	Experimental rooms	Xiamen, China	Subtropical climate	TT	[168]
Visual comfort and daylighting	Useful Daylight Illuminance (UDI)					
Cost	- Glazing initial cost (\$/m²) - Maintenance costs - Payback period - Net present value (NPV) - Internal rate of return (IRR) - Annual energy cost savings	Sunroom	Chongqing, China	Monsoonal humid subtropical climate	TC	[169]
Energy	- Cooling energy savings - Heating energy savings					
Visual comfort and daylighting	- Glare reduction efficiency (%) - Illuminance levels (lux)					

Thermal comfort	• SHGC • Indoor temperature reductions (°C) in summer. • Indoor temperature retention (°C) in winter.					
Visual comfort and daylighting	• Colour-rendering index (CRI) • Correlated colour temperature (CCT)	Experimental room	--	--	PDLC, SPD	[170]
Visual comfort and daylighting	• Daylight autonomy (DA) • Useful Daylight Illuminance (UDI) • Daylight Glare Probability (DGP)	Office	South of Belgium	Maritime temperate	EC	[171]
Opto-thermal properties	• Solar transmittance • Solar Reflectance • SHGC • U-value (W/m²K) • VLT					
Thermal comfort	• Indoor operative temperature					
Thermal comfort	• Indoor temperature • Indoor and outdoor surface temperature of glazing	Office	Lisbon, Portugal	Mild Mediterranean climate	PC	[49]
Opto-thermal properties	• U-value (W/m²K) • Solar factor (g-value) • Solar transmittance • Solar Reflectance • VLT • Visible reflectance • UV transmittance • UV absorptance					
Visual comfort and daylighting	• DGI • DGP • UDI					
Opto-thermal properties	• U-value • solar factor, <i>g</i> • solar transmittance • solar transmittance • Visible transmittance • Visible reflectance	University floor	Lisbon, Portugal	Mild Mediterranean climate	EC, TC	[172]
Thermal comfort	• Indoor temperature • Predicted Mean Vote (PMV)					
Opto-thermal properties	• U-value • Solar transmittance • Solar reflectance • Visual transmittance • Visual reflectance • Front side Infrared hemispherical emissivity • Back side Infrared hemispherical emissivity	Office room	Xiamen, China	Subtropical climate	TT	[129]
Visual comfort and daylighting	• UDI					
Energy	• Heating Energy consumption • Cooling Energy consumption • Lighting Energy consumption • Energy use intensity					
Thermal comfort	• PMV • PPD					
Opto-thermal properties	• U-value • SHGC • Total heat gain of glazing	Experimental setup	Najran, Saudi Arabia	Desert climate	PDLC and SPD	[173]
Thermal comfort	• Glazing surface temperature					
Energy	• Carbon emission mitigation (kg-CO₂/kWh)					
Opto-thermal properties	• U-value • G-value • Solar transmittance • Solar reflectance	Office room	Lisbon	Hot summer/mediterranean Climate	PC	[53]

	- Visual transmittance - Visual Reflectance - Visual Absorption - UV transmittance - UV absorptance					
Visual comfort and daylighting	- Illuminance (horizontal, vertical) - UDI					
Thermal comfort	- Air temperature - Surface temperature - Relative humidity - Solar radiation (Diffuse, global)					
Opto-thermal properties	- U-value (W/m2K) - g-value - VLT	Office	Athens, Greece	True Meditteranean	EC, TC	[174]
Visual comfort and daylighting	DGI					
Cost	- Glazing unit cost - Glazing installation cost - Glazing operating cost - Net Present Value (NPV)					
Energy	- Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Total annual energy consumption					
Opto-thermal properties	- U-value (W/m2K) - Solar transmittance - Solar reflectance - Visual transmittance - Visual Reflectance - Visual Absorption	Experimental model	New Delhi and London	Humid subtropical climate (New Delhi), Temperate oceanic climate (London)	GC	[175]
Thermal comfort	- Heat gain through glazing (kWh) - Heat Transfer to Air (kWh) - Solar radiation transmitted through window surface (W/m2)					
Cost	- Payback period (PBP) - Net present value (NPV) - Internal rate of return (IRR)					
	Glazing thickness					
Energy	- Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Total annual energy consumption					
Opto-thermal properties	- g-value - SHGC	Tower, Hotel	Dubai	Desert climate	EC, SPD	[176]
Energy	Total annual energy consumption					
Energy	- Heating energy consumption (kWh/year) - Total annual energy consumption (kWh/year)	Apartment s block (Mixed use)	Birmingham, UK	Temperate maritime climate	EC, GC	[177]
Opto-thermal properties	- U-value (W/m2K) - SHGC - VLT					
Thermal comfort	Indoor temperature					
Opto-thermal properties	- U-value (W/m2K) - SHGC - Solar transmittance - Solar reflectance - g-value - Visible transmittance - Visible reflectance - IR-transmission - IR-emissivity	Office building	Saudi Arabia	Hot climate region	PDLC	[178]
Visual comfort and daylighting	- Special Daylight Autonomy (sDA_{300lx}) - Annual Sun Exposure (ASE_{>1000lx, 250h}) - Useful daylight illuminance (UDI) - Indoor illuminance					

Thermal comfort	Glazing surface temperature					
Energy	- Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Total energy consumption - CO2 emission reduction (%)					
Energy	- Energy Use Intensity (EUI) - Heating Energy consumption - Cooling Energy consumption - Lighting Energy consumption - Annual Energy Savings	Office spaces	Boulder, CO	Semi-arid	EC	[179]
Opto-thermal properties	- SHGC - U-value - VLT					
Visual comfort and daylighting	UDI					
Opto-thermal properties	- U-value - SHGC - Solar transmittance - Solar reflectance - Visible transmittance - Visible reflectance - Infrared transmittance - Infrared hemispherical emissivity	Office room	Xiamen, China	Subtropical climate	TC	[180]
Visual comfort and daylighting	Useful daylighting illuminance (UDI)					
Energy	- Electric energy consumption for cooling - Electric energy consumption for heating - Electric energy consumption for Lighting - Total electric energy consumption (kWh/m²/Year)					
Opto-thermal properties	- SHGC - U-value - Solar Transmittance - Solar Reflectance - Solar Absorptance - VLT	Office	Sohag governor ate, Egypt	Hot desert	EC, GC, TC	[72]
Visual comfort and daylighting	Daylight Illuminance (lux)					
Energy	- Cooling energy consumption - Heating energy consumption - Lighting energy consumption					
Thermal comfort	Solar gain through glazing (kWh)					
Visual comfort and daylighting	- VLT - Correlated Color temperature (CCT) - Colour rendering index (CRI) - Colour fidelity (R_f) - Colour gamut (R_g)	Highly glazed buildings	Not mentioned-general study	--	EC, TC, PC, GC, SPD, LCD	[181]
Opto-thermal properties	- SHGC - U-value W/(m² K) - VLT	University laboratory	Rende, Italy	Warm and temperate	PC	[50]
Visual comfort and daylighting	- Daylight Autonomy (DA) - Useful Daylight Illuminance (UDI)					
Thermal comfort	- Solar irradiances transmitted by the windows (W/m²) - Solar radiation transmittance (kWh/m²)					
Energy	- Heating monthly energy consumption (kWh) - Cooling monthly energy consumption (kWh) - Lighting monthly energy consumption (kWh) - Total energy consumption (kWh/yr)					

Opto-thermal properties	- Solar Transmittance - Solar Reflectance - U (W/m²K) - SHGC - Visible Transmittance - Visible Reflectance - Emissivity	Office building	Brindisi and Milan, Italy	Humid subtropical climate	PC	[182]
Energy performance	- Cooling energy consumption - Heating energy consumption - Lighting energy consumption					
Visual comfort and daylighting	- Useful Daylight Illuminance (UDI) - Daylight Glare Index (DGI)					
Energy	- Cooling energy consumption - Heating energy consumption - Lighting energy consumption - Total annual energy consumption - Energy saving ratio (ESR) - CO2 emissions reduction (%)	Commercial	Benguerir, Morocco	Semi-arid (extremely hot during the summer)	TC, EC	[151]
Thermal comfort	- Predicted mean vote (PMV) - Predicted percentage of dissatisfaction (PPD)					
Visual comfort and daylighting	- Daylight illuminance (E_v) - Spatial Daylight Autonomy (sDA) - Useful daylight index (UDI) - Direct glare percentage (DGP)					
Cost	- Glazing initial cost - Payback period (PBP) - Energy-saving cost - Total annual energy saving					
Opto-thermal properties	- VLT - SHGC - Near-infrared radiation (NIR)	Office	Beijing, Shanghai and Guangzhou (China)	Cold zone (Beijing), Hot summer & cold winter (Shanghai), Hot summer & warm winter (Guangzhou)	TC	[183]
Energy	- Total energy consumption (kWh) - Total Energy savings					
Visual comfort and daylighting	- UDI - Illuminance					
Opto-thermal properties	- U-factor (W/m²K) - SHGC - Solar transmittance - VLT	Commercial room	Sao Paulo, Curitiba, Recife, Brazil	Humid subtropical (Sao Paulo), Humid subtropical – oceanic (Curitiba), Tropical (Recife)	EC	[184]
Visual comfort and daylighting	Indoor illuminance (lux)					
Thermal comfort	- Percentage of comfort (%) - Thermal comfort hours (h)					
Energy	- Heating energy demand - Cooling energy demand - Relative energy performance index (%)					
Energy	- Annual energy consumption (kWh/m²) - Annual cooling energy consumption - Energy saving rate (%) - Annual building total carbon emissions (kg/m²·yr) - Annual building total carbon reducing rate (%)	Commercial building	Miami, LA, Baltimore, Chicago, Denver, Duluth (USA)	Tropical monsoon (Miami), (LA) Semi-arid, Humid subtropical (Baltimore), Humid continental (Chicago)	EC	[185]
Thermal comfort	- Outdoor air temperature - Room air temperature - Solar radiation incident on the window - Global horizontal solar irradiance					
Opto-thermal properties	- U-value (W/m² K) - SHGC - VLT					
Cost	- Annual utility cost - Annual utility Cost saving per window area					

Thermal comfort	- Solar transmission - Glass surface temperature - Indoor air temperature	Test cell	Najran, KSA	Hot-arid climate	PDLC	[76]
Visual comfort and daylighting	- VLT - Correlated colour temperature (CCT) - Colour rendering index (CRI)					
Health and well being	- Solar material protection factor (SMPF) - Solar skin protection factor (SSPF)					
Opto-thermal properties	- U-value (W/m^2) - K (W/m^2C) - SHGC	Test cell	Saudi Arabia	Hot and desert	PDLC	[186]
Thermal comfort	- Heat transfer through conduction - Steady-state heat conduction through the system QSIWG - Thermal resistance of the system ($^{\circ}C/W$) RSIWG - Surface temperature of glass (inside, outside) - Indoor air temperature					
Opto-thermal properties	- SHGC - U-Value (W/m^2K) - Solar Transmittance - Solar Reflectance - Visible transmittance - Visible reflectance	Office test cell	Palermo, Italy	Mediterranean climate (Hot summer)	TT	[187]
Thermal comfort	- Total annual window heat gain (W/m^2) - Incident solar radiation - Outdoor temperatures - Indoor temperatures					
Energy	- Cooling energy consumption - Heating energy consumption - Lighting energy consumption - Total Annual energy consumption					
Opto-thermal properties	- SHGC - U-Value (W/m^2K) - VLT	Office building	Sohag governorate, Egypt	Hot desert	EC, GC, TC	[188]
Visual comfort and daylighting	Internal daylight illuminance (lux)					
Energy	- Cooling energy consumption (kWh) - Cooling energy saving ratio (%)					
Opto-thermal properties	- Visible Transmittance - Visible Reflectance - Solar Modulation (ΔT_{sol}) - Solar transmittance - Solar reflectance - Solar absorptance	Office building	Cairo, Barcelona, London	Desert climate (Cairo), Mediterranean (Barcelona), Oceanic climate (London)	TC	[189]
Visual comfort and daylighting	UDI					
Technical	Glazing thickness					
Energy	- Cooling energy consumption (kWh/m²) - Heating energy consumption (kWh/m²) - Lighting energy consumption (kWh/m²) - Annual energy consumption (kWh/m²) - Annual Energy Saving (%)					
Thermal comfort	- Annual window heat gain (kW/m²) - Incident solar radiation (W/m^2) - Heat gain during the hottest month - Heat gain during the coldest month	Office	New York, Hong Kong	Humid subtropical, heating dominated (New York), Sub-tropical (Hong Kong)	TC	[190]
Opto-thermal properties	- Visible Transmittance - Visible Reflectance - Solar transmittance - Solar reflectance - IR emissivity (inner)					
Visual comfort and daylighting	UDI					
Energy	- Cooling energy consumption (kWh/m²) - Heating energy consumption (kWh/m²)					

	• Lighting energy consumption (kWh/m2) • Annual energy consumption (kWh/m2) • Ventilation (fan) energy consumption (kWh/m2) • Heating energy savings (%) • Cooling energy savings (%) • Lighting energy savings (%) • Annual total energy savings (%)					
Technical	• Switching behavior					
Energy	• Cooling energy consumption (kWh/m2) • Heating energy consumption (kWh/m2) • Lighting energy consumption (kWh/m2)	Office	Riyadh-KSA, Incheon-South Korea, Moscow-Russia	Hot desert (Riyadh), Humid subtropical (Incheon), warm-summer humid continental (Moscow)	EC	[191]
Opto-thermal properties	• SHGC • U-Value (W/m²K) • Solar transmittance • Solar reflectance • Visible Transmittance • Visible Reflectance					
Visual comfort and daylighting	• DGI • Daylight interior illuminance					
Visual comfort and daylighting	• Horizontal illuminance (lux)					
Energy	• Cooling energy consumption (kWh/m2) • Heating energy consumption (kWh/m2) • Annual energy consumption (kWh/m2)	Building model	Anderson, South Carolina	Warm and temperate	EC	[192]
Opto-thermal properties	• SHGC • VLT					
Opto-thermal properties	• SHGC • U-Value (W/m²K) • VLT	Commercial and Residential 1	16 sub-regions, U.S.	Moist, dry, Marine	EC	[193]
Visual comfort and daylighting	• Daylight glare index (DGI) • Insolation (amount of solar radiation received per unit area)					
Energy	• Cooling energy consumption (kWh/m2) • Heating energy consumption (kWh/m2) • Annual energy consumption • Annual energy savings					
Cost	• Annual energy cost savings per ft² of window area					
Visual comfort and daylighting	• Illuminance • Daylight factor	Office building	Catania, Milan, Paris Italy	Dry-summer subtropical (Catania), Humid subtropical (Milan), Oceanic (Paris)	TC	[194]
Opto-thermal properties	• k (W/m·K) • U (W m⁻² K⁻¹) • Solar transmittance • Solar reflectance • Emissivity • Visible Transmittance • Visible Reflectance					
Technical	• Glazing Thickness • Switching temperature					
Energy	• Cooling energy consumption (kWh/m2) • Heating energy consumption (kWh/m2) • Lighting energy consumption (kWh/m2) • Annual energy consumption (kWh/m2 yr)					
Thermal comfort	• Operative temperature					

Appendix 2

(Identified categories and their corresponding indicators from SLR- Round-1)

Category (main criteria)	Frequency of Occurrence	Indicator (Sub-criteria)	Frequency of Occurrence	% across all indicators
Opto-thermal properties	37	Visible Light Transmittance (VLT)	32	6.26%
		Visible reflectance	14	2.74%
		Visible absorptance	2	0.39%
		Solar Heat Gain Coefficient (SHGC)	26	5.09%
		Solar transmittance	19	3.72%
		Solar reflectance	17	3.33%
		Solar absorptance	3	0.59%
		U-Value	28	5.48%
		g-value	6	1.17%
		Shading Coefficient (SC)	1	0.20%
		k-value	3	0.59%
		Infrared transmittance	3	0.59%
		Infrared hemispherical emissivity	8	1.57%
		Near-Infrared Radiation (NIR)	1	0.20%
		UV transmittance	2	0.39%
		UV absorptance	2	0.39%
		Solar modulation	1	0.20%
Energy	35	Cooling energy consumption	23	4.50%
		Heating energy consumption	21	4.11%
		Lighting energy consumption	19	3.72%
		Total energy consumption	22	4.31%
		Energy Use Intensity (EUI)	4	0.78%
		Energy consumption for smart glazing operation	1	0.20%
		Embodied energy	2	0.39%
		Cooling energy savings	4	0.78%
		Heating energy savings	2	0.39%
		Lighting energy savings	2	0.39%
		Total energy savings	10	1.96%
		CO ₂ emission	1	0.20%
		CO ₂ mitigation	6	1.17%
		Pre-use phase energy (MJ/m ²)	1	0.20%
		Net use-phase energy (MJ/m ²)	1	0.20%
		Net post-use phase energy (MJ/m ²)	1	0.20%
		Total Life cycle energy	1	0.20%
		Urban heat island (UHI) reduction	1	0.20%
		Relative energy performance index (%)	1	0.20%
		Ventilation (fan) energy consumption	1	0.20%
Visual comfort and daylighting	36	Spatial Daylight autonomy (sDA300lux)	7	1.37%
		Continuous Daylight Autonomy (DAcon)	1	0.20%
		Maximum Daylight Autonomy (DAmax)	1	0.20%
		Daylight factor (DF)	2	0.39%
		Useful Daylight Illuminance (UDI)	21	4.11%
		Daylight Glare Index (DGI)	8	1.57%
		Daylight Glare Probability (DGP)	7	1.37%
		Glare reduction efficiency (%)	1	0.20%
		Daylight Availability (DAv)	1	0.20%
		Colour rendering index (CRI)	7	1.37%
		Correlated Colour temperature (CCT)	7	1.37%
		Illuminance uniformity	2	0.39%
		Average annual daylight illuminance/indoor illuminance/ illuminance level	10	1.96%
		Horizontal illuminance	3	0.59%
		Vertical illuminance	2	0.39%

		Annual Sunlight Exposure (ASE1000/250h)	2	0.39%
		Circadian Stimulus Potential (CS)	1	0.20%
		Equivalent Melanopic Lux (EML)	1	0.20%
		Indirect non-visual effect of light – Circadian	1	0.20%
		Colour fidelity (Rf)	1	0.20%
		Colour gamut (Rg)	1	0.20%
Thermal comfort	26	Total heat gain of glazing	17	3.33%
		PMV	6	1.17%
		PPD	3	0.59%
		Indoor temperature/Indoor operative temperature	13	2.54%
		Glazing surface temperature	7	1.37%
		Percentage of comfort (%)	1	0.20%
		Thermal comfort hours (h)	1	0.20%
		outdoor temperature	2	0.39%
		Heat Transfer to Air (kWh)	1	0.20%
		Relative humidity	1	0.20%
		Internal heat gains	1	0.20%
		Light-to-solar gain ratio (LSG)	1	0.20%
		Solar heat flux through glazing (kWh/m2)	1	0.20%
		Incident solar radiation (W/m2)	3	0.59%
		Steady-state heat conduction through the system QSIWG	1	0.20%
		Thermal resistance of the system (°C/W) RSIWG	1	0.20%
Cost	13	Glazing per unit cost	10	1.96%
		Glazing maintenance costs	2	0.39%
		Glazing installation cost	2	0.39%
		Glazing operating cost	1	0.20%
		Glazing transportation fees	1	0.20%
		Glazing Replacement cost (\$/m2)	2	0.39%
		Glazing Disposal cost (\$/m2)	2	0.39%
		Total lifecycle cost	1	0.20%
		Payback period	6	1.17%
		Net present value (NPV)	5	0.98%
		Internal rate of return (IRR)	4	0.78%
		Cost of energy consumption for SG operation	1	0.20%
		Cooling energy consumption cost	1	0.20%
		Lighting energy cost	1	0.20%
		Building total Energy consumption cost	3	0.59%
		Cooling energy savings	1	0.20%
		Total energy savings	4	0.78%
Technical	9	Switching time	2	0.39%
		Glazing thickness	4	0.78%
		Actuation	1	0.20%
		Durability	1	0.20%
		Fuel/power/Energy requirement for opaque state	4	0.78%
		Commercial maturity level	1	0.20%
		Design Efficiency/capabilities.	2	0.39%
		Glazing color in its tinted states	1	0.20%
Life cycle environmental impacts	1	Light transmittance levels (e.g., 1%, 6%, 40%, 58%.)	1	0.20%
		Acidification (kg SO2 eq)	1	0.20%
		Eutrophication (kg PO4 P-lim)	1	0.20%
		Global warming potential (kg CO2 eq)	1	0.20%
		Non-renewable energy (MJ primary)	1	0.20%
		Ozone layer depletion (kg CFC-11 eq)	1	0.20%
Health and well being	1	Terrestrial acid/nutria (kg SO2 eq)	1	0.20%
		Solar material protection factor (SMPF)	1	0.20%
		Solar skin protection factor (SSPF)	1	0.20%

Appendix 3

(Questionnaire)

Smart Glazing Sustainability Criteria: Evaluation Form

Background and Purpose

- **STUDY TITLE**

DEVELOPMENT OF A SUSTAINABILITY ASSESSMENT FRAMEWORK FOR SMART GLAZING IN NON-DOMESTIC BUILDINGS

- **PURPOSE**

This study aims to create a comprehensive **Sustainability Assessment Framework (SG-SAF)** to guide the selection of the most sustainable smart glazing solutions for commercial buildings, especially in hot climates. The framework will evaluate smart glazing technologies across Environmental, Social, Economic, and Technical dimensions. **"Smart glazing"** refers to a type of glass or window system that can dynamically change its properties, such as tint, transparency, or heat transmission, in response to external stimuli or user control. This adaptability allows smart glazing to optimize daylighting, solar heat gain, and energy efficiency in buildings, contributing to improved occupant comfort and reduced energy consumption."

- **SURVEY FOCUS**

We have identified key sustainability criteria and sub-criteria under the mentioned sustainability dimensions. We invite your expert input to review and rate their importance in selecting smart glazing for sustainable buildings. Your feedback will help ensure the SG-SAF is both comprehensive and practical. Briefly, through this survey, we expect experts to

1. **Rate** the perceived importance of identified criteria and sub-criteria in selecting smart glazing for sustainable buildings.
2. **Ensure** that the selected criteria effectively capture the critical sustainability aspects of smart glazing.
3. **Assess** the practicality of these criteria for real-world applications.

- **TARGET AUDIENCE**

We welcome participation from professionals and experts with expertise in any of the following key areas:

- Sustainable Building Design and Construction
- Advanced or Smart Glazing Systems and Technologies
- Building Envelopes and Facades
- Energy Efficiency and Building Performance
- Energy-Efficient buildings
- Building Lifecycle Assessment and Environmental Impact
- Building Codes and Regulations
- Smart or Sustainable building materials
- Or related expertise

Your contribution is vital in shaping a robust and effective Sustainability Assessment Framework for smart glazing!

Smart Glazing Sustainability Criteria: Evaluation Form

* Required

Participant Details

1

Name *

Enter your answer

2

Email *

Enter your answer

3

Organization *

Enter your answer

4

Title/Position *

Enter your answer

5

Areas of expertise *

Enter your answer

6

Years of experience *

Enter your answer

Smart Glazing Sustainability Criteria: Evaluation Form

Guidelines (Important for completing the survey)

Please review each criterion and sub-criterion listed in the table below.

- **Rating**

Assign a rate to each criterion and sub-criterion based on its perceived importance in your decision-making process when selecting **smart glazing systems** for **commercial buildings** in hot climates. Use the following scale:

- **1 = Not Important**
- **2 = Slightly Important**
- **3 = Moderately Important**
- **4 = Very Important**
- **5 = Extremely Important**

*First, you need to assign the rating to each criterion identified under the following sustainability dimensions.
Environmental: Env, Social: Soc, Economical: Eco, Technical: Tec*

Second, you will assign the rating to each sub-criteria identified under specific criteria

- **Feedback**

In the "Feedback" section, please provide any additional comments or suggestions you have regarding each sustainability dimension. Feel free to:

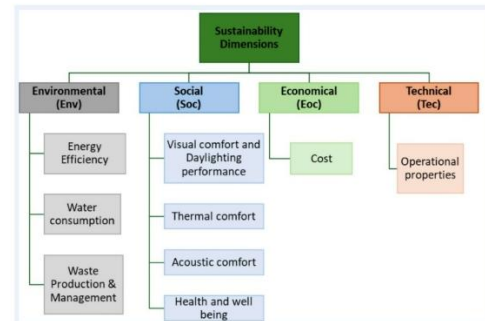
- **Suggest** modifications or elaborations to the existing criteria or sub-criteria
- **Propose** new criteria or sub-criteria that you believe are important but not currently included
- **Highlight** any potential overlaps or redundancies between criteria
- **Share** any specific challenges or opportunities related to each criterion that you have encountered in your projects.

You are welcome to focus on the listed criteria, but also feel free to suggest new ones or provide any other insights that you believe would contribute to a more comprehensive and effective framework

Smart Glazing Sustainability Criteria: Evaluation Form

* Required

Rate the identified criteria mentioned under each sustainability dimension.



Rate the criteria based on their **perceived importance in selecting** the most sustainable smart glazing

7

Brief Description of Each Criteria:

- 1. Energy Efficiency:** It evaluates smart glazing's ability to reduce energy consumption in building
- 2. Water Consumption:** It assesses the water footprint associated with the smart glazing's life cycle, including manufacturing and maintenance, important in water-scarce regions.
- 3. Waste Production and Management:** It evaluates the environmental impacts associated with the production, use, and end-of-life disposal of smart glazing, including waste generation and resource depletion.
- 4. Visual Comfort and Daylighting:** It assesses the ability of smart glazing to provide adequate and comfortable daylighting while minimizing glare and visual discomfort.
- 5. Thermal Comfort:** It evaluates the smart glazing's contribution to maintaining a comfortable indoor thermal environment.
- 6. Acoustic Comfort:** It assesses the sound insulation properties of smart glazing, contributing to a quieter indoor environment.
- 7. Occupant Health:** It evaluates the impact of smart glazing on occupant health and well-being, considering factors like UV transmittance
- 8. Cost:** This criterion assesses the financial implications of adopting smart glazing, including the initial investment, installation, operation, maintenance, and potential energy savings.
- 9. Operational Performance:** It assesses the technical aspects of smart glazing, including switching speed, energy requirements, durability, and controllability

*

	Not Important	Less Important	Moderate	Important	Very Important
Energy Efficiency (En-1)	☐	☐	☐	☐	☐
Water Consumption (En-2)	☐	☐	☐	☐	☐
Waste Production and Management (En-3)	☐	☐	☐	☐	☐
Visual Comfort and Daylighting Performance (S-1)	☐	☐	☐	☐	☐
Thermal Comfort (S-2)	☐	☐	☐	☐	☐
Acoustic Comfort (S-3)	☐	☐	☐	☐	☐
Health and Well-being (S-4)	☐	☐	☐	☐	☐
Cost (Ec-1)	☐	☐	☐	☐	☐
Operational Performance (T-1)	☐	☐	☐	☐	☐

8

1. **Modify or elaborate** on the existing criteria
2. **Propose new criteria** that you believe are important but not currently included
3. **Highlight any potential overlaps** or redundancies between criteria
4. **Add** any comment

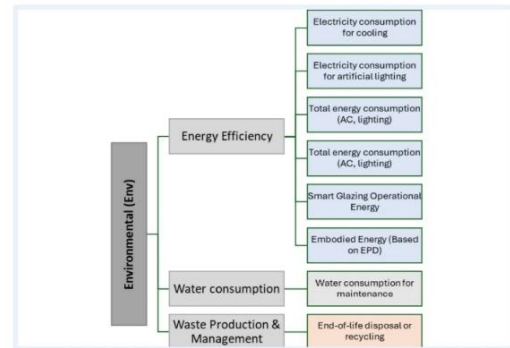
Enter your answer

Smart Glazing Sustainability Criteria: Evaluation Form

* Required

Rate the identified sub-criteria:

Environmental



Rate the identified sub-criteria under each criteria of **Environmental dimension**

9

Rank each sub-criteria of **"Energy efficiency."** *

Description of each sub-criteria:

1. **Electricity Consumption for Heating:** Measures the energy used for heating due to heat loss through glazing.
2. **Electricity Consumption for Cooling:** Evaluates energy needed for cooling by reducing solar heat gain.
3. **Electricity Consumption for Artificial Lighting:** Assesses the energy used for lighting, optimized by daylighting through smart glazing.
4. **Total Energy Consumption (AC, Lighting):** Represents combined energy for air conditioning and lighting impacted by glazing.
5. **Total Energy Savings:** Quantifies the overall energy reduction compared to conventional glazing.
6. **Smart Glazing Operational Energy:** Measures energy required to operate and maintain smart glazing functionality.
7. **Embodied Energy:** Total energy consumed in manufacturing smart glazing from raw materials.
8. **CO2 Mitigation:** Estimates CO2 reduction from lower cooling energy consumption with smart glazing.

	Not Important	Less Important	Moderate	Important	Very Important
Electricity consumption for heating	☐	☐	☐	☐	☐
Electricity consumption for cooling	☐	☐	☐	☐	☐
Electricity consumption for artificial lighting	☐	☐	☐	☐	☐
Total energy consumption (AC, lighting)	☐	☐	☐	☐	☐
Total energy savings	☐	☐	☐	☐	☐
Smart glazing operational energy	☐	☐	☐	☐	☐
Embodied energy	☐	☐	☐	☐	☐
CO2 mitigation	☐	☐	☐	☐	☐

10

Rate each sub-criteria of "**Water consumption.**" *

Description of sub-criteria:

1. Water consumption for maintenance: Quantifies the water needed for cleaning and upkeep of the smart glazing throughout its lifespan. Relevant in hot, arid climates where water scarcity is a concern.

	Not Important	Less Important	Moderate	Important	Very Important
Water consumption for maintenance	☐	☐	☐	☐	☐

11

Rate each sub-criteria of "**Waste Production and Management.**" *

Description of sub-criteria

1. **End-of-life disposal or recycling:** Assesses options for disposal, recycling, or repurposing at the glazing's end of life.

	Not Important	Less Important	Moderate	Important	Very Important
End-of-life disposal or recycling	☐	☐	☐	☐	☐

12

1. **Modify or elaborate** on the existing sub-criteria
2. **Propose new sub-criteria** that you believe are important but not currently included
3. **Highlight any potential overlaps** or redundancies between sub-criteria
4. **Add** any comment

Enter your answer

Rate the identified sub-criteria: **Social**

Rate the identified sub-criteria under each criteria of **Social dimension**

13

Rate each sub-criteria of "**Visual comfort and Daylighting performance.**" *

Description of each sub-criteria:

1. **Visible light transmittance (VLT):** Percentage of visible light passing through the glazing, impacting daylighting and views.
2. **Visible reflectance:** Percentage of visible light reflected by the glazing, affecting aesthetics, glare, and privacy.
3. **Glare index/Daylight glare index (DGI):** Measures the potential for discomfort glare from daylight. Lower values indicate better glare control.
4. **Daylight autonomy (DA):** Percentage of occupied hours with sufficient daylight to reduce electric lighting.
5. **Daylight factor:** Ratio of indoor to outdoor illuminance, indicating daylight penetration.
6. **Uniformity of daylight illuminance:** Measures how evenly daylight is distributed within a space.
7. **Useful daylight illuminance (UDI):** Percentage of occupied hours with comfortable daylight levels (not too dim or too bright).
8. **Daylight glare probability (DGP):** Predicts the likelihood of occupants experiencing glare.
9. **Color rendering index (CRI):** Measures how accurately colors are rendered under the transmitted light.
10. **Correlated color temperature (CCT):** Describes the color appearance of light (warm to cool).

	Not Important	Less Important	Moderate	Important	Very Important
Visible Light transmittance (VLT)	☐	☐	☐	☐	☐
Visible reflectance	☐	☐	☐	☐	☐
Glare index / Daylight glare index (DGI)	☐	☐	☐	☐	☐
Daylight autonomy (DA)	☐	☐	☐	☐	☐
Daylight factor	☐	☐	☐	☐	☐
Uniformity of daylight illuminance	☐	☐	☐	☐	☐
Useful daylight illuminance (UDI)	☐	☐	☐	☐	☐
Daylight glare probability (DGP)	☐	☐	☐	☐	☐
Color rendering index (CRI)	☐	☐	☐	☐	☐
Correlated color temperature (CCT)	☐	☐	☐	☐	☐

14

Rate each sub-criteria of "**Thermal comfort.**" *

Description of each sub-criteria:

1. SHGC: Measures solar heat admitted, lower is better for hot climates.

2. U-Value: Rate of heat transfer, lower indicates better insulation.

3. Solar Transmittance: Fraction of solar energy passing through.

4. Solar Reflectance: Proportion of solar energy reflected.

5. Solar Energy Absorptance: Fraction of solar energy absorbed, affecting glazing temperature.

6. Infrared Transmittance (IR): Infrared radiation passing through.

7. Infrared hemispherical Emissivity: measure of a material's ability to emit absorbed heat as infrared radiation

8. Predicted Mean Vote (PMV): Predicts average occupant thermal sensation (-3 cold to +3 hot).

9. Predicted Percentage of Dissatisfied (PPD): Estimates percentage of people likely uncomfortable.

10. Annual Window Heat Gain: Total solar heat through windows over a year.

11. Indoor Temperature: Refers to the temperature inside the building, influenced by glazing and solar control.

12. Light-to-Solar Gain Ratio (LSG): Measures the balance of daylight with heat gain, higher is better.

	Not Important	Less Important	Moderate	Important	Very Important
Solar heat gain coefficient (SHGC)	☐	☐	☐	☐	☐
U-Value	☐	☐	☐	☐	☐
Solar transmittance	☐	☐	☐	☐	☐
Solar reflectance	☐	☐	☐	☐	☐
Solar energy absorption	☐	☐	☐	☐	☐
Infrared transmittance (IR)	☐	☐	☐	☐	☐
Infrared hemispherical emissivity	☐	☐	☐	☐	☐
Predicted Mean Vote (PMV)	☐	☐	☐	☐	☐
Predicted Percentage of Dissatisfied (PPD)	☐	☐	☐	☐	☐
Annual window heat gain	☐	☐	☐	☐	☐
Indoor temperature	☐	☐	☐	☐	☐
Light-to-solar gain ratio (LSG)	☐	☐	☐	☐	☐

15

Rank each sub-criteria of "**Acoustic comfort.**" *

Description of each sub-criteria:

1. Sound Transmission Class (STC): A standardized measure of sound insulation, quantifying how effectively the glazing blocks sound transmission.

2. Noise Reduction Index: A regulated measure of sound insulation, specifically evaluating the reduction in noise levels achieved by a building material.

	Not Important	Less Important	Moderate	Important	Very Important
Sound Transmission Class (STC)	☐	☐	☐	☐	☐
Noise Reduction Index	☐	☐	☐	☐	☐

16

Rate each sub-criteria of "**Health and well-being.**" *

Description of sub-criteria

1. UV transmittance: It refers to the amount of ultraviolet (UV) light that passes through smart glazing.

	Not Important	Less Important	Moderate	Important	Very Important
UV transmittance	☐	☐	☐	☐	☐

17

1. **Modify or elaborate** on the existing sub-criteria
2. **Propose new sub-criteria** that you believe are important but not currently included
3. **Highlight any potential overlaps** or redundancies between sub-criteria
4. **Add** any comment

Rate the identified sub-criteria: **Economical**

Rate the identified sub-criteria under each criteria under **Economical dimension**

18

Rate each sub-criteria of "**Cost.**" *

Description of each sub-criteria:

1. **Initial Cost (Glazing unit cost):** The total expenses incurred to purchase, transport, and install a glazing system.
2. **Operating cost of glazing:** Includes the costs associated with energy consumption for the operation of smart glazing.
3. **Savings in air conditioning:** Reduction in expenses associated with air conditioning when existing glazing is replaced with smart glazing alternatives.
4. **Payback period (PBP):** The time it takes for the energy savings to cover the initial investment cost.
5. **Cooling cost saving:** Reduction in expenses associated with cooling when existing glazing is replaced with smart glazing alternatives.

	Not Important	Less Important	Moderate	Important	Very Important
Initial cost /Glazing unit cost	☐	☐	☐	☐	☐
Operating cost of glazing	☐	☐	☐	☐	☐
Savings in Air conditioning	☐	☐	☐	☐	☐
Payback Period (PBP)	☐	☐	☐	☐	☐
Cooling cost saving	☐	☐	☐	☐	☐

19

1. **Modify or elaborate** to the existing sub-criteria
2. **Propose new sub-criteria** that you believe are important but not currently included
3. **Highlight any potential overlaps** or redundancies between sub-criteria
4. **Add** any comment

Rate the identified sub-criteria: **Technical**

Rate the identified sub-criteria under each criteria under **Technical dimension**

20

Rate each sub-criteria of "**Operational Performance.**" *

Description of each sub-criteria:

1. Transition Speed: The time it takes for the smart glazing to change its transparency or opacity.

2. Degree of Transparency: The level of transparency or opacity achievable by the smart glazing.

3. Actuation: The mechanism used to change the glazing's properties (e.g., electrical, thermochromic).

4. Energy/Power Requirement for Glazing State: The energy or power needed to change or maintain the glazing's state (e.g., opaque or tinted).

5. Durability: The life expectancy of the smart glazing.

6. Resilience: The glazing's ability to withstand harsh environmental conditions like high temperatures, intense sunlight, and dust.

7. Commercial Maturity Level: The technology's market readiness and availability, influence its practicality and cost-effectiveness.

	Not Important	Less Important	Moderate	Important	Very Important
Switching time/Transition speed	☐	☐	☐	☐	☐
Degree of transparency	☐	☐	☐	☐	☐
Actuation	☐	☐	☐	☐	☐
Energy /Power requirement for glazing state	☐	☐	☐	☐	☐
Durability	☐	☐	☐	☐	☐
Resilience	☐	☐	☐	☐	☐
Commercial maturity level	☐	☐	☐	☐	☐

21

1. **Modify or elaborate** to the existing sub-criteria
2. **Propose new sub-criteria** that you believe are important but not currently included
3. **Highlight any potential overlaps** or redundancies between sub-criteria
4. **Add** any comment

Enter your answer

22

Kindly add comments, suggestions, or feedback.

Enter your answer

23

Which of the following types of **Smart glazing** are you familiar with? Please select all that apply.

- ☐ Smart glazing or smart windows in general
- ☐ Electrochromic
- ☐ Polymer Dispersed Liquid Crystal (PDLC)
- ☐ Suspended Particle Device (SPD)
- ☐ Thermochromic
- ☐ Thermotropic
- ☐ Photochromic
- ☐ Gasochromic
- ☐ None

24

Will you be available to participate as an expert in the second phase of this research? *

<https://forms.office.com/r/nykKGh2uXR?origin=lprLink>

Appendix 4

Table 69: Detailed profile of survey respondents

ID	Title/ Position	Organization	Organization Type	Region	Years of experience	Areas of expertise
1	Associate Professor	KFUPM	Academic institution	KSA	20	- Advanced building envelopes - Acoustics & noise control in buildings
2	Associate Professor	King Faisal University	Academic institution	KSA	36	Construction & Sustainable management
3	Professor	KFUPM	Academic institution	KSA	24	Sustainable architecture
4	Professor/Dean	KFUPM	Academic institution	KSA	30	- Building thermal & energy analysis - Building envelope thermal & moisture performance - IEQ - Sustainable envelope design
5	Director/Architect	BluKube Architecture	Architectural firm	Australia	18	High performance buildings
6	Director/Architect	Ravi Urban Development Authority	Development authority	Pakistan	13	Architect
7	PhD candidate	Queensland University of Technology	Academic institution	Australia	7	- LCA - BIM - Energy efficiency - Carbon emission assessment
8	Principle Architect	Aknan Engineering Consultants	Design and Engineering consultancy	KSA	6	Built environment
9	Associate Facade Consultant	FMDC	Design and Engineering consultancy	UK	9	Facade engineering
10	Associate Professor	Eindhoven University of Technology	Academic institution	Netherlands	14	-
11	Professor	Aror University, Sukkur	Academic institution	Pakistan	15	Architecture & Urbanism
12	CEO/Founder	ADD digital design	Architectural firm	Somalia	5	- Architecture design - Computational design - Urban design
13	Postdoctoral Researcher	Delft University of Technology	Academic institution	Netherlands	6	- Material efficiency & reuse - Material science
14	Postdoctoral Researcher	Delft University of Technology	Academic institution	Netherlands	6	Smart facades & buildings
15	Officer Associate-Architecture	Ravi Urban Development Authority	Development authority	Pakistan	4	Architecture
16	Managing Director	GreenWay Green Building Consultancy	Green building consultancy	UAE	13	Sustainability specialist
17	CEO	TheSheltaGroup	Construction company	Nigeria	30	Architecture

ID	Title/ Position	Organization	Organization Type	Region	Years of experience	Areas of expertise
						• Sustainable design & Construction
18	Professor	University of California, Berkeley	Academic institution	USA	41	• Building science • Sustainability
19	Assistant Professor	Nippon Institute of Technology	Academic institution	Japan	6	• Architectural environmental engineering • Thermal environment
20	Building Performance Analyst	dbHMS	Sustainability focused engineering consultancy	Mexico	13	• Building performance analyst
21	Sustainability Consultant	Stantec	Design and Engineering consultancy	Colorado	10	• Green & Sustainable buildings
22	Assistant Professor	Delft University of Technology	Academic Institution	Netherlands	20	• Sustainable architecture • Energy-efficient facade design • Refurbishment strategies for buildings

Vitae

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Publications:

- (2024). *Industry 4.0 digital technologies for the advancement of renewable energy: Functions, applications, potential and challenges. Energy Conversion and Management: X.* <https://doi.org/10.1016/j.ecmx.2024.100779>
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