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Regulatory Gap in Fenestration Thermal Performance: Integrating Linear Thermal Transmittance into Energy Codes in Cooling-Dominated Climates

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Abstract

Fenestration systems play a critical role in building thermal performance, particularly in cooling-dominated climates where envelope inefficiencies directly amplify electricity demand. In Saudi Arabia and other Gulf Cooperation Council (GCC) countries, cooling accounts for the majority of building energy consumption. Nevertheless, the façade and insulated glass industries are experiencing rapid market expansion. Despite this technological evolution, prevailing regulatory frameworks, including the Saudi Building Code (SBC), ASHRAE 90.1, and the International Energy Conservation Code (IECC), primarily rely on area-weighted U-values and solar heat gain coefficients (SHGC), without explicitly integrating multidimensional thermal bridge effects such as linear thermal transmittance (ψ). This paper investigates the structural omission of ψ within current energy compliance systems, evaluates its implications in cooling-dominated climates, and proposes a phased regulatory integration pathway aligned with sustainability objectives under Vision 2030. Literature synthesis indicates that thermal bridges may increase cooling loads by up to 25% and total building energy use by 5–30%, while remaining structurally omitted from compliance metrics. The findings highlight the need to transition from simplified prescriptive compliance toward physics-informed governance capable of addressing evolving façade complexity in hot-arid environments. The proposed framework offers a systematic pathway for integrating linear thermal transmittance requirements while supporting regional sustainability goals and the advancement of high-performance building technologies.

Keywords: linear thermal transmittance; thermal bridges; fenestration; cooling-dominated climates; building energy codes; sustainability governance; Vision 2030; GCC regulations

1. Introduction

1.1. Fenestration Systems in Building Energy Performance

Fenestration systems are among the most thermally vulnerable components of the building envelope, significantly influencing overall energy consumption and occupant comfort. In cooling-dominated climates, buildings experience persistent thermal stress driven by high ambient temperatures, intense solar radiation, and extended cooling seasons [1]. The building sector in hot-arid regions such as Saudi Arabia accounts for approximately 75% of total electrical energy consumption, with cooling demand accounting for the dominant share of electricity use [2]. Research indicates that temperature increases significantly amplify cooling loads, underscoring the sensitivity of energy systems to envelope Performance and emphasizing the necessity of accurate thermal assessment methodologies.

While glazing technologies have evolved considerably toward insulated glass units (IGUs), low-emissivity (Low-E) coatings, thermally broken frames, and curtain wall assemblies, regulatory compliance frameworks have largely retained simplified evaluation approaches. Most energy codes assess window performance using area-weighted U-values and solar heat gain coefficients (SHGC), without explicit integration of multidimensional heat transfer effects occurring at glazing-frame interfaces. This structural simplification may lead to significant performance discrepancies between nominal compliance values and actual thermal behavior in cooling-dominated climates [3].

1.2. Research Questions and Study Objectives

This study addresses three fundamental research questions that guide the literature review and analysis. First, it examines the extent to which current energy codes explicitly evaluate linear thermal transmittance (ψ) in fenestration systems. Second, it examines how this omission affects performance reliability in cooling-dominated climates characterized by the rapid expansion of the façade market. Third, it explores what a phased regulatory framework can integrate thermal bridge evaluation while supporting sustainability objectives under Vision 2030 [4].

This study positions linear thermal transmittance not merely as a thermal parameter, but as a governance variable that mediates the relationship between façade complexity and national energy resilience.

1.3. Significance for Sustainability and Vision 2030

The rapid expansion of the Saudi façade and glazing market further amplifies the importance of accurate thermal bridge evaluation. Saudi Arabia's Vision 2030 emphasizes sustainable development through economic diversification and energy-efficiency initiatives. Research demonstrates that optimizing building envelope design can support these sustainability goals by reducing reliance on energy-intensive cooling systems, offering significant environmental and economic benefits. Understanding and addressing regulatory blind spots in thermal performance assessment is therefore essential for achieving national climate objectives [2,5].

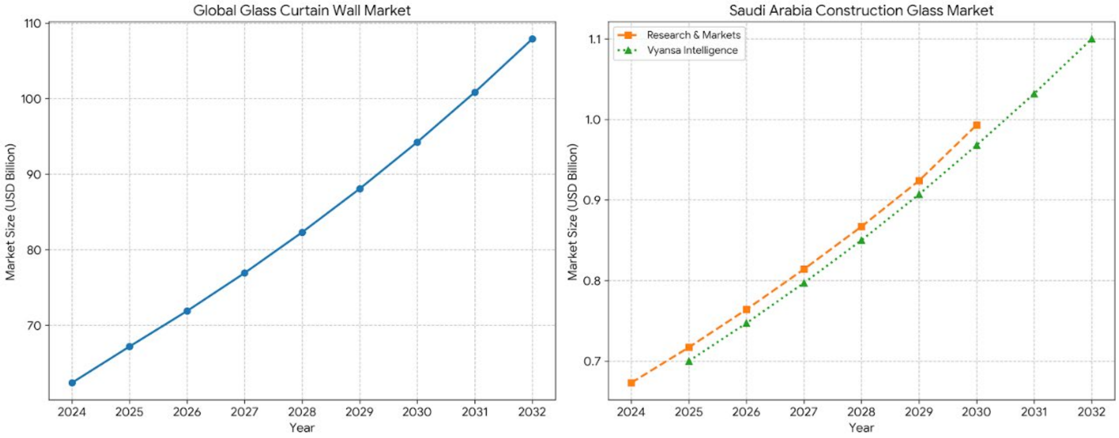

Figure 1. Comparative Analysis of Global and Saudi Arabian Construction Glass Markets.

The side-by-side visualization contrasts the absolute scale and projected growth of the global glass curtain wall market against the regional Saudi Arabian construction glass sector. Global Market Trends: The left panel displays the global glass curtain wall market, which is valued at USD 62.4 billion in 2024 and is projected to reach USD 107.91 billion by 2032. This consistent upward trajectory reflects a robust global demand for advanced, energy-efficient building envelopes. The right panel illustrates the construction glass market in Saudi Arabia, which is projected to grow from approximately USD 0.67 billion in 2024 to USD 1.1 billion by 2032, according to Vyansa Intelligence. The regional expansion is primarily driven by massive infrastructure developments and a transition toward high-performance glazing technologies, mandated by the Saudi Building Code (SBC) and Vision 2030 sustainability targets. The rapid expansion of the Saudi façade and glazing industry further intensifies the importance of accurate performance assessment. While the Saudi market remains significantly smaller in absolute scale relative to the global curtain wall sector, its growth trajectory closely mirrors global expansion rates, underscoring the Kingdom's accelerating infrastructure development, giga-projects under Vision 2030, and increasing adoption of energy-efficient glazing technologies [6–8].

Unlike previous studies that focus primarily on technological mitigation strategies or simulation-based optimization, this study reframes thermal bridge omission as a governance and regulatory design issue, particularly in cooling-dominated economies undergoing rapid façade market expansion. Unlike prior technical optimization studies, this research develops a structured comparative regulatory evaluation combined with analytical scenario modeling to quantify the systemic implications of ψ omission in cooling-dominated climates.

1.4. Theoretical Framework and Quantification Methods

Thermal bridges at window installations significantly affect the energy performance and indoor comfort of buildings, particularly in nearly zero-energy buildings (nZEB) [9]. Linear thermal transmittance (ψ-value) quantifies additional heat losses occurring at junctions between building components, representing heat flow that simplified one-dimensional U-value calculations cannot capture [10].

Numerical calculations of heat flux through building structure joints have become increasingly relevant due to EU requirements for nearly zero energy buildings. Window installation perimeters are particularly problematic, where frame fastenings to load-bearing structures create linear thermal bridges. Calculations performed using specialized software in accordance with ISO 10211 [11] standards demonstrate that ψ-values can range widely from 0.025 W/(m·K) to -0.005 W/(m·K) for top and side installations, with optimal installation depths of 9-15 cm depending on the insulation layer thickness [12]. Negative ψ-values may occur when insulation overlap results in localized thermal improvement.

A critical comparison of thermal bridge calculation methods reveals significant variation in predicted heat losses across methodologies. Research examining whole-building thermal bridges compared multiple techniques, including simplified regulatory methods, ISO 14683 [13]catalogs, national catalogs, two-dimensional thermal modelling, and conjugate heat and moisture simulation. Overall heat losses varied by 30% depending on the calculation method, with linear heat losses ranging between 12% to 32% of surface heat losses. The evaluation demonstrated that simplified methods produced the lowest heat losses, while ISO 14683 [13]produced the highest results, with numerically simulated results falling between the two [14,15].

Fenestration systems exhibit multidimensional heat transfer behavior due to the interaction between glazing layers, spacer bars, frames, and structural interfaces. Unlike opaque walls, window assemblies involve significant two-dimensional conductive effects, particularly at glazing edges.

The overall heat transfer coefficient of a window is typically expressed by Eqn (1):

$$U_{window} = \frac{A_g U_g + A_f U_f + L\psi}{A_{total}} \qquad (1)$$

where:

- U_g= glazing transmittance
- U_f= frame transmittance
- A_g, A_f= glazing and frame areas
- L= length of glazing–frame interface
- ψ= linear thermal transmittance

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Linear thermal transmittance represents additional heat flow not captured by area-weighted terms alone. In high-performance glazing systems, ψ may contribute a non-negligible proportion of total thermal loss.

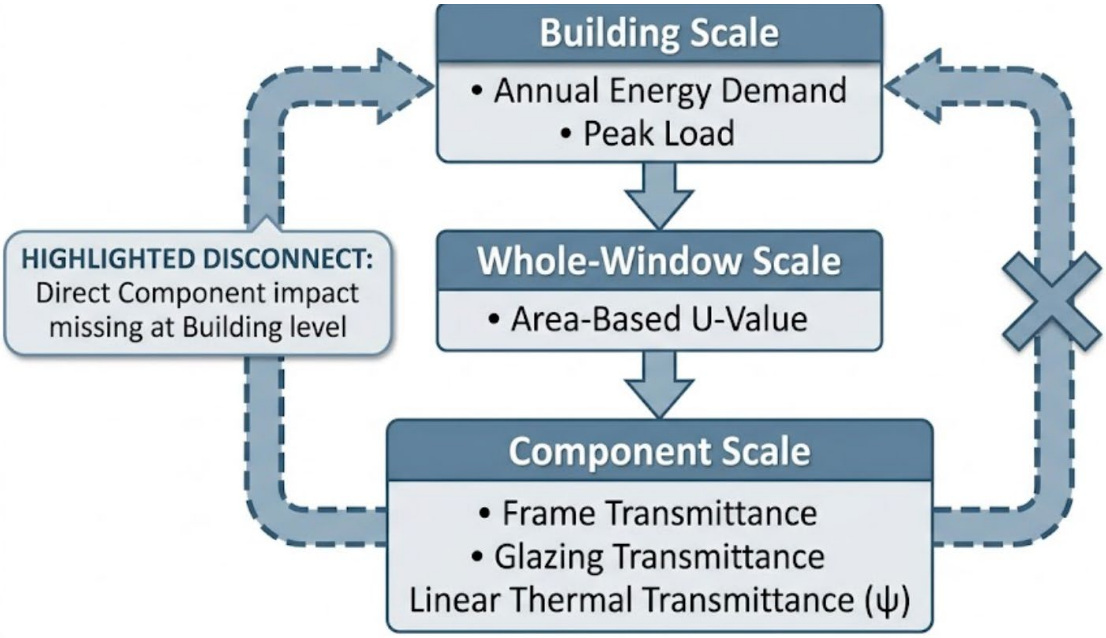


Figure 2. Multi-scale thermal performance evaluation in fenestration systems.

Hierarchical representation of building-scale energy demand, whole-window U-value assessment, and component-level parameters including frame transmittance (U_f), glazing transmittance (U_g), and linear thermal transmittance (ψ), illustrating multidimensional heat transfer effects.

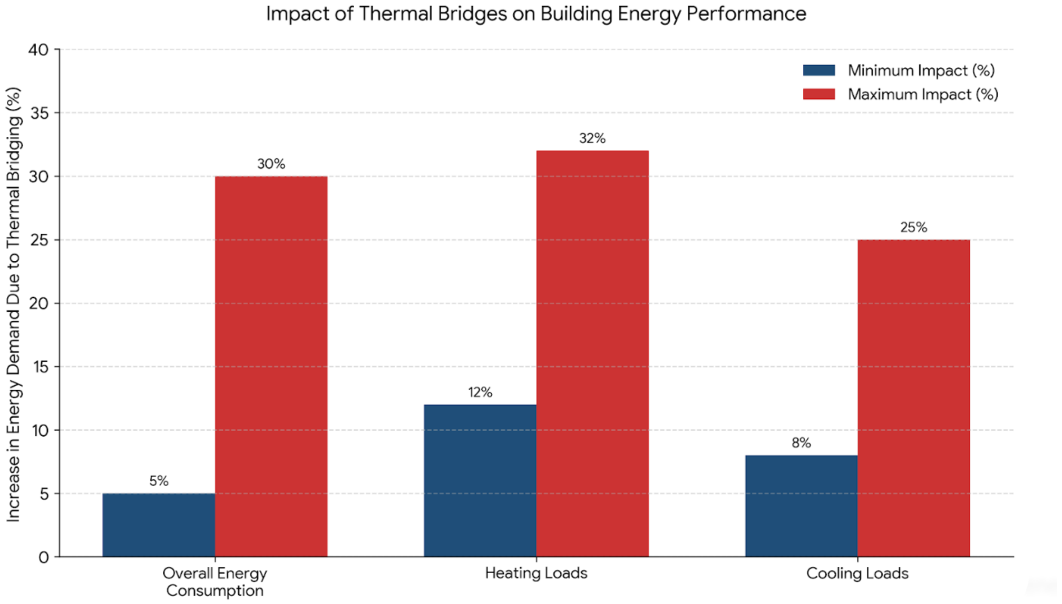
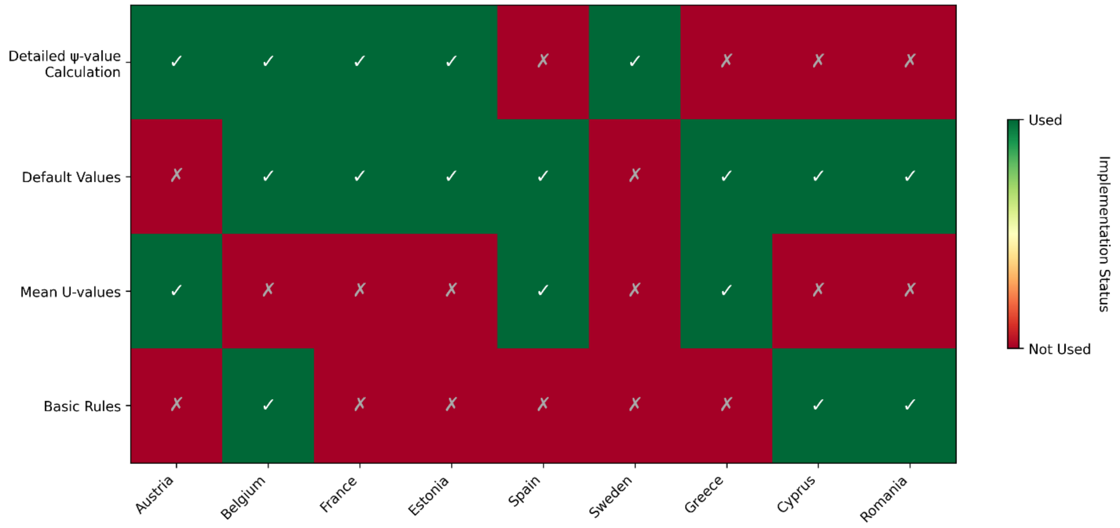


Figure 3. Impact of thermal bridges on building energy consumption (range reported in literature: 5–30%). Source: Alvur et al. (2026) [10].

As shown in **Figure 3**, Thermal bridging can significantly influence building energy performance, with reported increases in overall energy consumption ranging from approximately 5% to 30%. The effect is particularly pronounced in heating-dominated conditions, where energy demand may increase by up to 32%. In comparison, cooling loads may rise by as much as 25% depending on façade configuration and insulation continuity. These findings underscore the importance of mitigating linear and point thermal bridges in high-performance building envelopes to achieve compliance with energy efficiency standards and sustainability targets [10].



	Austria	Belgium	France	Estonia	Spain	Sweden	Greece	Cyprus	Romania
Detailed ψ-value Calculation	✓	✓	✓	✓	✗	✓	✗	✗	✗
Default Values	✗	✓	✓	✓	✓	✗	✓	✓	✓
Mean U-values	✓	✗	✗	✗	✓	✗	✓	✗	✗
Basic Rules	✗	✓	✗	✗	✗	✗	✗	✓	✓

Figure 4. Overview of thermal bridge calculation approaches applied in national energy performance assessment procedures across nine European countries, based on Kuusk et al. (2017) [16].

Figure 4 compares the implementation of thermal bridge calculation methods across selected European countries. It illustrates whether countries apply detailed ψ-value calculations, default values, mean U-values, or simplified basic rules in national energy performance assessments.
The results show considerable variation in methodological approaches, reflecting differences in regulatory frameworks and levels of calculation accuracy across Europe **[16]**.

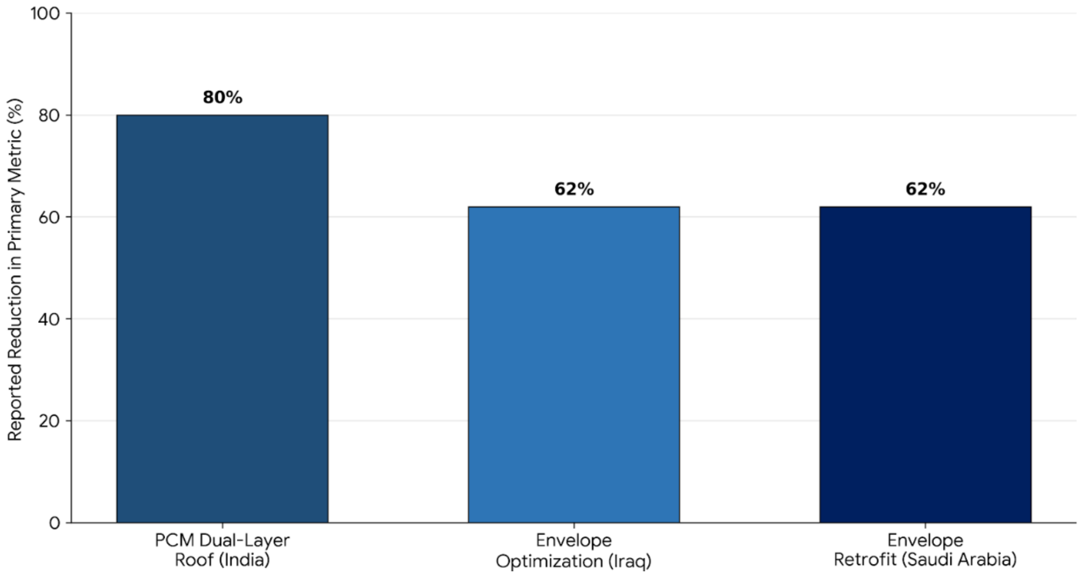


Figure 5. Comparative thermal performance improvements in Hot-Arid Climates, Data synthesized from Aloshan (2026) [17], Huluka & Muthulingam (2025) [18], and Aljashaami et al. (2025) [19].

Figure 5 presents thermal performance improvements in hot-arid climates based on individual case studies: PCM dual-layer roof (India), envelope optimization (Iraq), and envelope retrofit (Saudi Arabia). Percentages correspond to reductions in the primary performance metric reported in each study (heat flux, cooling load, or total energy demand) and are not directly comparable. The PCM-integrated dual-layer roof demonstrates the highest impact, achieving approximately 79.8% heat flux reduction under experimental conditions. Envelope optimization measures in Iraq show cooling load reductions of up to 62%, primarily through improved insulation and glazing strategies. Similarly, envelope retrofit strategies in Saudi Arabia report total annual energy consumption reductions of about 62%, highlighting the critical role of building envelope enhancement in achieving zero-energy targets. The percentages represent reported reductions in cooling load, heat flux, or total energy demand under hot-arid climate conditions.

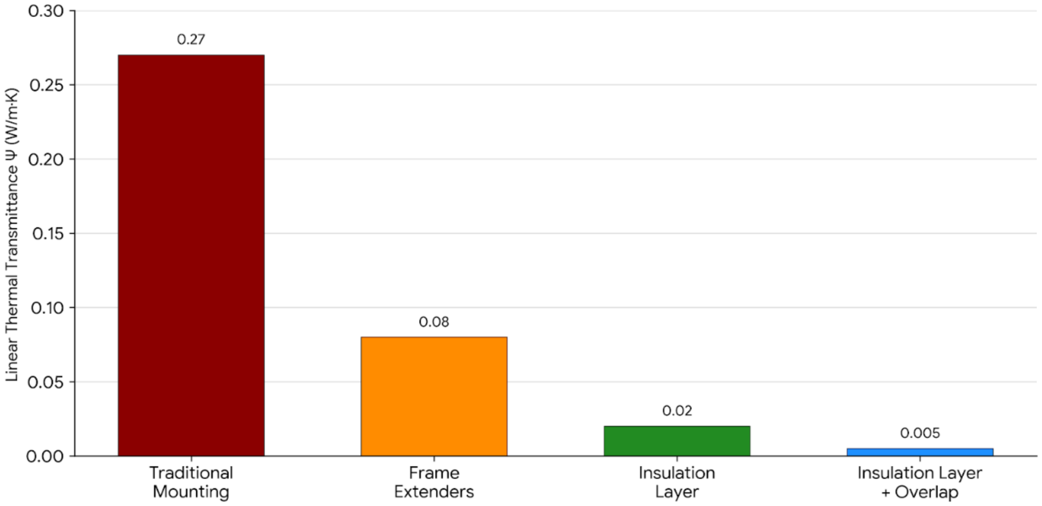


Figure 6. Impact of Window Mounting Position on Linear Thermal Transmittance (Ψ-value) Source: Gendelis et al. (2026) [9].

As shown in Figure 6, advanced installation methods significantly reduce thermal bridge intensity compared to traditional mounting. Data adapted from Gendelis et al. (2026) **[9].** Finite element method (FEM) simulations have become essential for evaluating thermal bridge effects in building envelopes. Studies using commercial 3D simulation software to estimate thermal losses demonstrate that linear thermal transmittance of thermal bridges and associated heat flux loss can decrease by more than 50% when proper mitigation measures are implemented [20]. Optimizing thermal insulation parameters through mathematical modelling enables the determination of optimal values based on energy-efficiency criteria, providing useful information for researchers, designers, and decision-makers [21].

Artificial intelligence approaches offer promising alternatives for thermal bridge analysis, with fuzzy systems demonstrating excellent performance in estimating linear heat transmittance coefficients. These AI-based approaches can reduce the need for time-consuming traditional calculations and expensive experiments while accurately determining ψ coefficients for cases not included in training data [22].

Collectively, these findings demonstrate that ψ-values represent a quantifiable and methodologically mature parameter whose exclusion from compliance frameworks is not due to technical limitations, but regulatory simplification.

2. Methodology

2.1. Research Design and Analytical Structure

This study adopts a comparative regulatory and analytical modeling research design to investigate the structural omission of linear thermal transmittance (ψ) in fenestration-related energy compliance frameworks. The methodology integrates regulatory evaluation, analytical heat transfer modeling, climate-context assessment, and governance pathway development into a unified analytical structure. Rather than conducting a narrative literature synthesis, the study is structured around the following core analytical layers:

- **Regulatory Structure Assessment**—identifying formal treatment of ψ within energy codes.
- **Thermal Performance Quantification**—evaluating the mathematical implications of ψ omission using standardized heat transfer formulations.
- **Climate Sensitivity Evaluation**—assessing amplification effects in cooling-dominated climates.
- **Regulatory Integration Modeling**—constructing a phased governance transition framework.

The research workflow proceeds sequentially such as (a), Identification of regulatory variables (b) Development of structured comparison matrix (c) Analytical scenario modeling (d) Climate amplification interpretation and (e) Governance pathway synthesis. This structured approach as shown in **Figure 7** ensures reproducibility and transparency in assessing compliance gap.

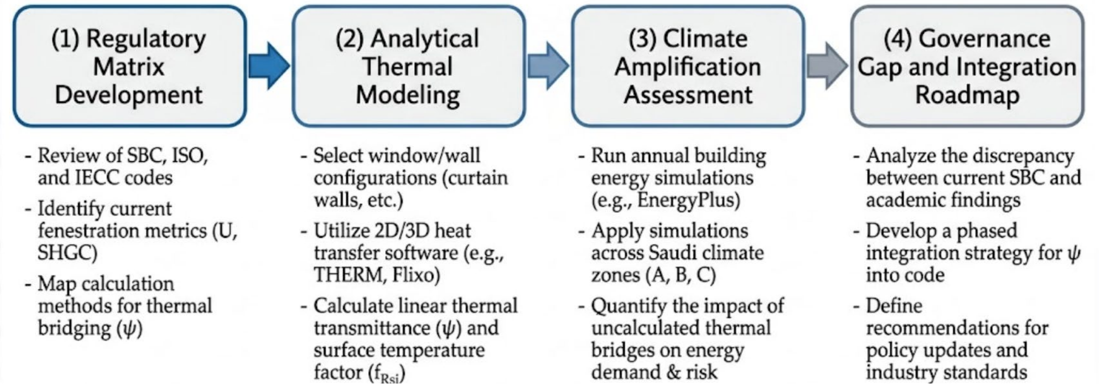


Figure 7. Research Methodology Framework for ψ Integration Study.

2.2. *Structured Comparative Regulatory Matrix Development*

A systematic comparative matrix was constructed to evaluate how major energy codes treat fenestration thermal performance and thermal bridge effects. Four frameworks were selected due to their relevance to GCC regulatory practice and international benchmarking such as (a) Saudi Building Code (SBC), (b) ASHRAE 90.1, (c) International Energy Conservation Code (IECC) and (d) EPBD-aligned European codes.

Each framework was evaluated across multiple analytical dimensions, including:

- Explicit requirement for ψ-value calculation
- Reference to ISO 10211 / ISO 14683
- Requirement for numerical 2D/3D modeling
- Treatment of installation-level thermal bridges
- Inclusion of ψ in the whole-window Uw formula
- Recognition of thermal bridge impact on peak load
- Climate adaptation orientation
- Alignment with nearly zero-energy building (nZEB) targets
- Verification stage (design vs as-built)

Each dimension was categorized using a qualitative classification system consisting of Explicitly required or not required, Implicitly embedded and Partially integrated. This matrix-based approach allows structural comparison rather than descriptive commentary. The analysis focuses on governance architecture rather than performance thresholds, enabling identification of systemic regulatory omission patterns.

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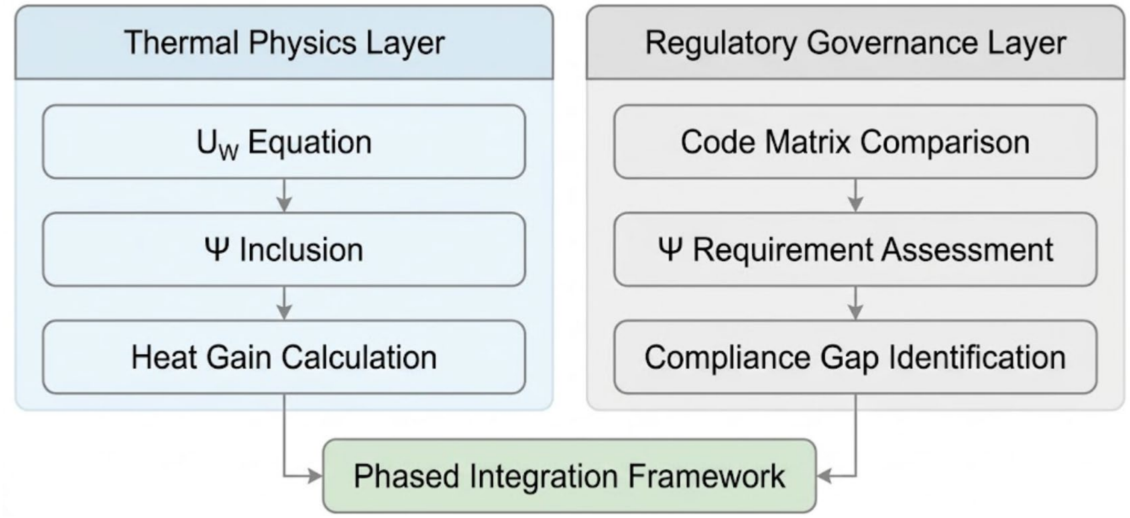

Figure 8. Integrated framework combining thermal physics modelling and regulatory compliance analysis for phased window thermal bridge mitigation.

The resulting comparative framework (**Table 2**) serves as the analytical foundation for diagnosing the regulatory discontinuity.

2.3. Climate Amplification and Governance Gap Modeling

To assess the systemic relevance of ψ omission in hot-arid environments, a climate amplification framework was applied. Cooling-dominated climates are characterized by high cooling degree days, prolonged peak load periods, elevated solar radiation, and large exterior–interior temperature gradients. Incremental heat gain attributable to ψ was evaluated using the steady-state heat transfer relation as shown by **Eqn (2):**

$$Q = U \cdot A \cdot \Delta T \quad (2)$$

Under elevated ΔT conditions, even small increases in effective U-value produce amplified cooling demand effects. This relationship was interpreted at three scales:

1. Component scale (window interface)
2. Façade scale (cumulative interface length)
3. Building scale (peak load implications)

To illustrate the thermal severity of cooling-dominated regions within Saudi Arabia, long-term average monthly ambient temperatures for representative cities across different climatic zones are presented in **Table 1**. The selected cities reflect inland desert climates (Riyadh, Guriat), coastal humid climates (Jeddah, Dahran), and elevated southwestern climates (Khamis Mushait), thereby capturing national climatic diversity.

Table 1. Long-Term Average Monthly Ambient Temperatures (°C) in Representative Saudi Cities [23].

Month	Madinah	Riyadh	Guriat	Khamis Mushait	Jeddah	Dahran
Jan	18.3	15.1	7.5	13.5	23.9	15.0
Feb	20.2	16.5	10.0	16.0	24.8	16.5
Mar	24.4	22.7	12.0	17.0	26.4	20.0
Apr	28.2	26.6	18.0	20.0	28.8	24.9
May	34.1	32.5	23.0	23.0	31.8	30.5
Jun	37.8	36.0	27.0	26.0	32.8	34.8
Jul	37.9	37.4	30.0	26.0	33.9	35.9
Aug	37.3	36.5	30.0	25.0	33.9	36.2
Sep	37.0	33.9	27.0	23.0	32.7	33.9
Oct	31.0	27.5	23.0	22.0	31.0	29.1

Nov	24.9	20.4	15.0	17.0	28.5	23.9
Dec	20.5	16.1	8.0	15.0	26.1	16.8

As shown in **Table 1**, peak summer temperatures exceed 37 °C in inland cities such as Madinah and Riyadh, while coastal regions such as Jeddah and Dahran exhibit persistently high ambient temperatures above 30 °C for extended periods. Even during winter months, several locations maintain moderate temperatures, indicating prolonged cooling demand seasons. The sustained high ΔT between exterior ambient conditions and conditioned indoor setpoints (typically 23–25 °C) amplifies envelope heat gain through both area-based and linear thermal transmittance components. Under such conditions, incremental ψ-related heat transfer becomes proportionally more significant in annual cooling load calculations.

For example, assuming an indoor setpoint of 24 °C, peak summer ΔT in Riyadh reaches approximately 13–14 °C during July–August, while in coastal Dahran ΔT remains above 10 °C for five consecutive months. Such sustained temperature differentials intensify cumulative linear heat transfer across façade interfaces.

Parallel to thermal modeling, a governance gap assessment was conducted by comparing Technological capability (availability of ISO-compliant ψ methods), Regulatory requirement presence, Market expansion indicators (façade complexity growth) and Sustainability targets under Vision 2030. This dual-layer (technical + governance) evaluation enables identification of a structural regulatory–market integration gap. Having established the technical and climatic implications of ψ omission, the following section evaluates how these parameters are formally treated within prevailing energy codes.

3. Regulatory Frameworks for Fenestration Assessment

The EPBD directive 2002 and its 2010 recast have led to significant efforts in Member States to improve building energy performance, with transmission characteristics playing a significant role in energy-efficient buildings. A review of thermal bridge treatment in energy calculation and compliance procedures across nine European countries reveals four main methods: detailed calculation based on linear thermal transmittance values, simple basic rules, default transmittance values, and mean U-values. Significantly, the review found that there are often no specific thermal bridge-related compliance procedures, with control mechanisms frequently ending at the building permit phase [16].

In the UAE, buildings consume more than 80% of total electrical generation, with cooling systems responsible for approximately 70% of buildings' peak load [24]. Despite having similar climate conditions and construction practices, green building regulations in Dubai, Abu Dhabi, and Ras Al Khaimah have different threshold requirements. For example, the maximum thermal transmittance (U-value) for exterior walls varies from 0.57 W/m²K in Dubai to 0.32 W/m²K in Abu Dhabi to 0.48 W/m²K in Ras Al Khaimah (refer **Table 2**). Constructed Nearly Zero Energy Buildings demonstrate U-values substantially lower than regulations, between 0.06-0.09 W/m²K, indicating significant gaps between minimum regulatory requirements and achievable performance [24].

Table 2. Comparison of Thermal Transmittance Requirements in GCC Regions (Source: [24]).

Region	Maximum Wall U-Value (W/m²K)	Thermal Bridge Requirements	Compliance Focus
Dubai	0.57	Not explicitly specified	Prescriptive
Abu Dhabi	0.32	Limited guidance	Prescriptive
Ras Al Khaimah	0.48	Not specified	Prescriptive
nZEB Examples	0.06-0.09	Detailed analysis	Performance-based

The general conclusion from international code analysis indicates that compliance frameworks need to be extended to assess as-built energy performance. This regulatory gap is particularly

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significant in the context of the rapid expansion of the façade market in the Gulf region, where sophisticated curtain wall and insulated glazing technologies are being deployed without corresponding regulatory provisions for multidimensional thermal assessment. The absence of explicit ψ-value requirements in prevailing codes, including the Saudi Building Code (SBC), ASHRAE 90.1, and the International Energy Conservation Code (IECC), creates a fundamental disconnect between available technology and regulatory expectations [25–27].

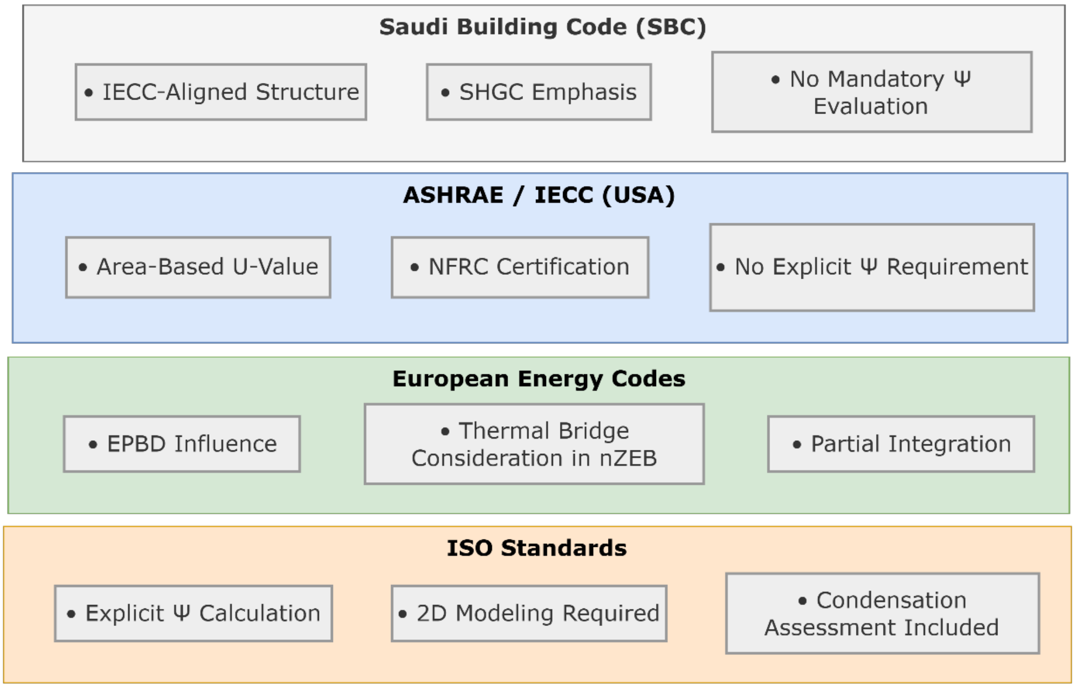

Figure 9. Comparative regulatory treatment of thermal bridge effects in fenestration systems.

Conceptual comparison of ISO 10077, ASHRAE 90.1, IECC, and Saudi Building Code (SBC) approaches to window thermal performance evaluation, highlighting the inclusion or omission of linear thermal transmittance (ψ).

Figure 9 provides a conceptual comparison of international regulatory approaches, highlighting the explicit inclusion of ψ-calculation in ISO-based methodologies and its omission in prescriptive frameworks such as ASHRAE 90.1, IECC, and SBC. This divergence illustrates the structural regulatory blind spot central to this study.

The comparative matrix (See **Table 3**) reveals a structural divergence between ISO-influenced European regulatory frameworks and prescriptive North American–derived codes adopted in the GCC region. While SBC, ASHRAE 90.1, and IECC emphasize area-weighted U-values and SHGC as primary fenestration compliance metrics, none explicitly mandate linear thermal transmittance (ψ) evaluation. In contrast, EPBD-aligned national codes increasingly require junction-level ψ-calculation using ISO 10211 methodologies, particularly in nearly zero energy building (nZEB) contexts. This discrepancy illustrates the governance gap underlying the systemic exclusion identified in cooling-dominated climates.

Table 3. Thermal Bridge Treatment in SBC, ASHRAE 90.1, IECC, and EPBD.

Dimension	SBC (Saudi Building Code)	ASHRAE 90.1	IECC	EPBD (EU Directive Framework)

Regulatory Philosophy	Prescriptive compliance largely aligned with the IECC structure	Hybrid (Prescriptive + Performance-based)	Primarily prescriptive with the performance path option	Performance-oriented, lifecycle-based framework
Climate Context Orientation	Cooling-dominated (hot-arid focus)	Multi-climate (US climate zones)	Multi-climate (US climate zones)	Mixed climates (heating-dominated emphasis historically)
Window Performance Metrics Required	Area-weighted U-value + SHGC	U-factor + SHGC (via NFRC certification)	U-factor + SHGC	U-value + thermal bridge consideration (varies by member state)
Explicit ψ (Linear Thermal Transmittance) Requirement	Not explicitly required	Not explicitly required	Not explicitly required	Required in many member states under EPBD implementation
Reference to ISO 10211 / 14683	No direct reference	Not referenced	Not referenced	ISO 10211 is commonly referenced for 2D modeling
Thermal Bridge Assessment Scope	Implicitly embedded in assembly U-value	Incorporated indirectly via tested assemblies	Not separately calculated	Often explicitly calculated at the junction level
Whole-Window Uw Formula Including ψ	Not mandated	Not mandated	Not mandated	Often required in nZEB contexts
Numerical 2D/3D Thermal Modeling Required	No	No	No	Frequently required for compliance
Condensation Risk Assessment	Limited	Limited	Limited	Often mandatory (surface temperature factor)
Treatment of Installation Effects	Not regulated	Not explicitly regulated	Not explicitly regulated	Often included in a detailed calculation
Compliance Pathways	Prescriptive tables	Prescriptive + Energy Cost Budget method	Prescriptive + Performance path	Performance-based national implementation
Recognition of Thermal Bridge Impact on Peak Load	Not explicitly	Not explicitly	Not explicitly	Indirectly through transmission loss calculations
Verification Stage	Design-stage compliance	Design-stage compliance	Design-stage compliance	Increasing emphasis on as-built Performance
Alignment with Nearly Zero Energy Building (nZEB)	Emerging	Partial alignment	Partial alignment	Strong alignment (mandatory under EPBD recast)
Market–Regulation Integration Level	Low (rapid façade market growth not	Moderate	Moderate	Higher (advanced façade integration in EU markets)

	matched by regulation)			
Regulatory Treatment of Multidimensional Heat Transfer	Simplified 1D assumption	Simplified 1D assumption	Simplified 1D assumption	Recognizes multidimensional heat flow
Cooling-Dominated Climate Adaptation	Focus on SHGC reduction	Balanced heating/cooling	Balanced heating/cooling	Historically heating-focused, expanding scope
Governance Maturity for ψ Integration	Early-stage	Developed but ψ omitted	Developed but ψ omitted	Advanced (in several member states)

4. Thermal Performance Challenges in Cooling-Dominated Climates

4.1. Unique Requirements of Hot-Arid Environments

Thermal performance, energy demand, and environmental sustainability in hot-arid climates where cooling loads dominate are strongly influenced by façade design. Research demonstrates that climate-responsive passive façade strategies represent an effective approach to enhancing energy efficiency and sustainability in hot-arid environments, with experimental comparisons showing average heat flux reductions of 11.35% through detached curtain wall configurations. The parametric optimization of building envelopes for energy efficiency in Taiwan's subtropical climates demonstrates that optimized insulation strategies can achieve annual cooling energy savings of 1-3% when modelled with realistic HVAC systems, with climate projections indicating 5.12-11.15% increases in future cooling demand by 2080 [28–31].

Studies on hot-arid climates reveal that solar transmittance (g-value) of windows plays a more important role than thermal transmittance (U-value) in reducing heat gain within interior spaces. In the UAE context, the choice of building materials significantly impacts a building's passive performance and carbon footprint, with the incorporation of 50 mm expanded polystyrene insulation into external walls demonstrating substantial reductions in cooling requirements [32].

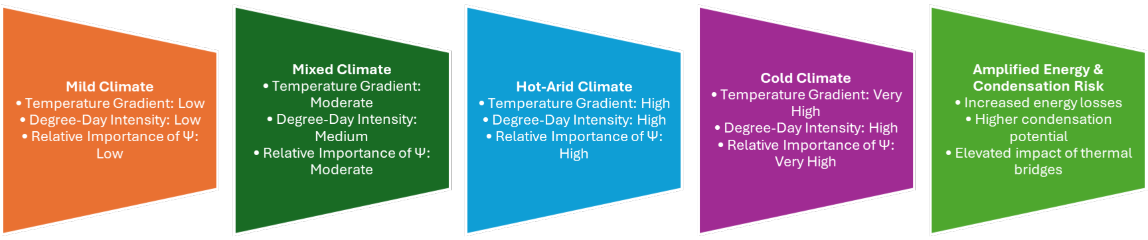

Figure 10. Climate amplification effect in cooling-dominated environments.

The interaction between climate severity, façade complexity, and regulatory simplification is conceptualized in Figure 10. In cooling-dominated environments, even marginal increases in envelope heat transfer may translate into disproportionately higher cooling loads, peak demand intensification, and grid stress. Although SHGC dominates peak solar gains, ψ-related conductive heat transfer contributes to cumulative cooling demand, particularly during non-solar load periods.

4.2. Window-to-Wall Ratio and Glazing Optimization

Research examining the impacts of window-to-wall ratio (WWR) on energy performance in Riyadh, Saudi Arabia, demonstrates that optimizing WWR to 25% reduced energy consumption by 5.6% and cooling loads by 7.5%. These findings, as shown in **Figure 11,** emphasize the critical role of building envelope design in enhancing energy efficiency, particularly in hot climates where balancing daylighting requirements with thermal insulation is essential. An evaluation of advanced glazing technologies for residential buildings in Jeddah reveals that 36mm aerogel glazing (U = 0.9 W/m²K, SHGC = 0.3) reduces annual cooling demand by 48.6% compared to single-pane glazing. Notably, 87% of these savings derive from SHGC reduction, with only 3.02 percentage points attributable to U-value improvements [33].

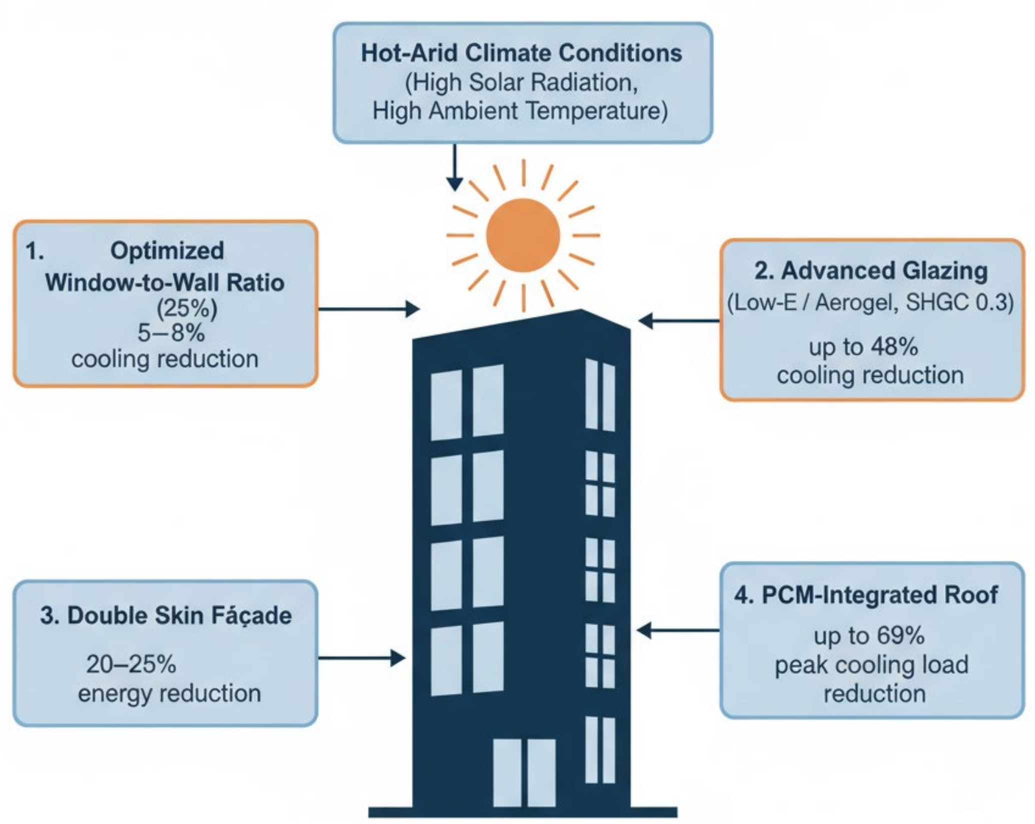

Figure 11. Cooling Energy Reduction Potential Through Building Envelope Optimization in Hot-Arid Climates.

4.3. Integration of Advanced Technologies

Double skin façades (DSF) have received increasing attention as alternatives to conventional glazed curtain walls for their ability to effectively reduce thermal transmittance (U-value) and solar heat gain (G-value). DSF design comprises assessments of building geometric factors, glazing type, ventilation procedures, shading devices, daylighting, and maintenance expenses [34]. Research on high-rise residential buildings in Abu Dhabi demonstrates that optimal DSF configurations with a 35 cm cavity depth, comprising a double-glazed single-skin layer and a Low-E exterior layer, can reduce overall energy consumption by over 25% [35].

Phase change materials (PCMs) integrated into building envelopes have significant potential to reduce cooling loads in hot climates. Studies examining spherical PCM modules embedded within reinforced concrete roofs demonstrate average reductions in indoor surface temperature of 10.2 °C and decreases in cooling load of up to 69%. These findings highlight the practical viability of PCM-integrated systems as passive cooling strategies for buildings in hot climates [36].

While Section 4 outlines climate-driven amplification mechanisms, the following case studies demonstrate how targeted fenestration strategies can mitigate these effects in practice.

5. Case Studies: Fenestration Performance and Energy Savings

5.1. Window Installation Optimization

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Research on window mounting position effects shows that relatively small changes in installation position can markedly reduce thermal bridging. The most effective strategy is to install windows within the insulation layer at an optimal depth of 7-12 cm, achieving ψ-value reductions from traditional values of 0.27 W/(m·K) to 0.02 W/(m·K). With frame overlap and frame extenders, ψ-values can be further reduced to 0.005 W/(m·K) in optimal configurations. In case studies of historical buildings retrofitted to the Passive House standard, installing windows in the insulation layer reduced annual heating demand from 32 kWh/m² to 24 kWh/m² [9].

5.2. Mitigation Technologies and Strategies

Cutting-edge technologies demonstrate considerable energy-saving potential for addressing thermal bridges in fenestration systems. As shown in **Table 4**, vacuum glazing with U-values as low as 0.2 W/(m²·K) and aerogel-filled frame cavities, reducing thermal permeability by 45%, represent significant technological advances. Furthermore, precise installation techniques can lower linear thermal transmittance (LTT) by up to 80%. A holistic approach integrating advanced glazing technologies, optimized frame materials, and meticulous installation methods offers a powerful solution to enhance window thermal efficiency.

Table 4. Thermal Bridge Mitigation Strategies for Fenestration Systems (Synthesis from Multiple Studies).

Mitigation Strategy	LTT Reduction	Energy Savings	Implementation Complexity
Vacuum Glazing	U < 0.2 W/m²K	22-30%	High
Aerogel Frame Cavities	45% permeability reduction	15-25%	Medium
Optimal Window Positioning	Up to 90–95%	20-25% heating	Medium
Thermally Broken Frames	60-80%	15-20%	Low-Medium
Precise Installation	Up to 80%	10-15%	Low

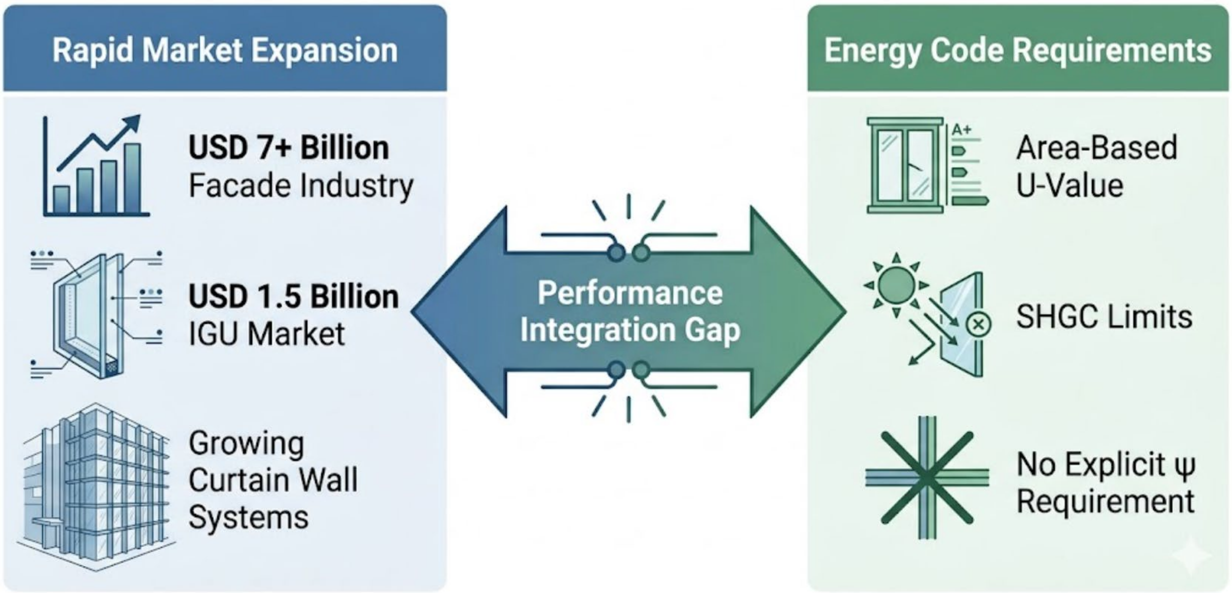

Figure 12. Market expansion versus regulatory integration gap.

Despite demonstrated mitigation potential, regulatory frameworks have not evolved proportionally to technological advancements. **Figure 12** illustrates the divergence between rapid façade market growth and continued reliance on simplified prescriptive metrics, producing a performance integration gap.

5.3. Retrofit and Near-Zero Energy Achievement

Achieving near-zero energy in hot climates requires comprehensive retrofitting approaches focused on building envelope optimization . Research on residential villas in Riyadh demonstrates that optimizing façade elements alone reduced annual energy consumption by 62%, from 60,641 kWh to 37,801 kWh. Integration of photovoltaic systems further decreased net annual energy consumption to 9,489 kWh, representing an 84% reduction compared to the base case. These findings align with the sustainability objectives of Saudi Vision 2030 and demonstrate the transformative potential of envelope-focused retrofit strategies [37–40].

6. Proposed Regulatory Integration Framework

6.1. Phased Approach to Code Revision

The transition from simplified prescriptive compliance toward physics-informed governance requires a systematic, phased approach. This framework should address the regulatory-market performance gap identified in current energy compliance systems while aligning with sustainability objectives under Vision 2030. The proposed pathway involves initial capacity building, followed by pilot implementation, and culminating in mandatory compliance requirements for thermal bridge assessment in fenestration systems.

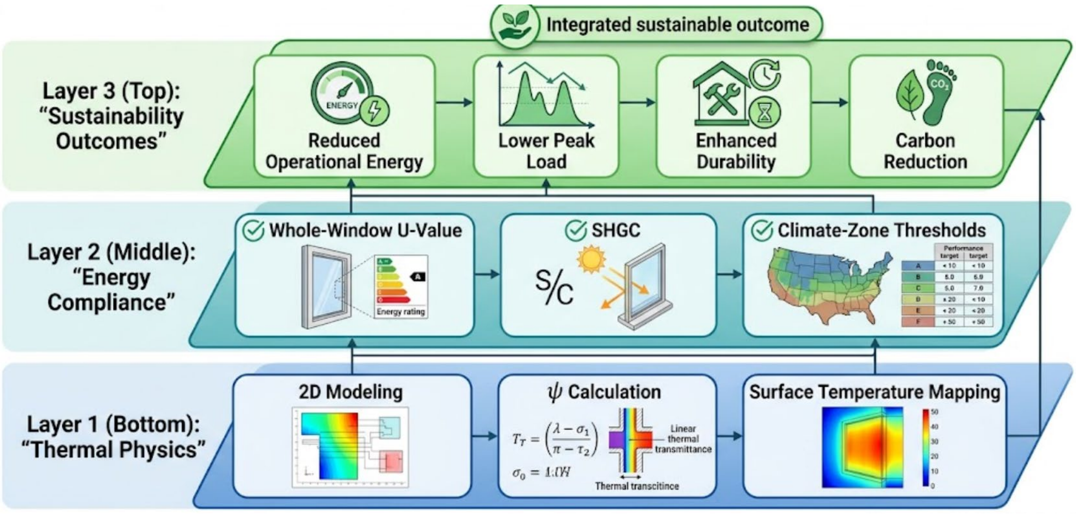

Figure 13. Integrated sustainable façade evaluation model.

To operationalize the transition toward physics-informed governance, a three-layer evaluation structure is proposed (**Figure 13**), linking component-level ψ-calculation, assembly-level compliance metrics, and building-scale sustainability outcomes.

The phased implementation pathway illustrated in **Figure 14** provides a structured regulatory transition model, progressing from voluntary ψ-reporting to full performance-based compliance integration.

Research demonstrates that implementing government-funded building energy efficiency programs is highly cost-effective, potentially reducing annual electricity consumption by 11,000 GWh and peak demand by 2,500 MW, with over 4,000 jobs created during ten-year implementation periods. These macro-economic benefits support the case for regulatory advancement in the GCC context [41].

6.2. Technical Requirements and Standards Adoption

The integration of thermal bridge evaluation into regulatory frameworks requires the adoption of standardized calculation methodologies. ISO 10211 provides the foundation for numerical modeling approaches, while ISO 14683 offers simplified catalogue-based methods suitable for initial implementation phases. The application of building performance simulation tools integrated with BIM workflows enables a comprehensive assessment of envelope thermal performance, including thermal bridge effects [42–44]. To facilitate systematic adoption within national building codes, a structured implementation pathway is necessary. As summarized in **Table 5**, the proposed phased regulatory integration framework outlines a progressive transition from voluntary awareness-building measures toward full mandatory compliance. The staged approach allows capacity development, industry training, and methodological standardization to mature before full enforcement is introduced. Such a framework reduces implementation risk while ensuring long-term regulatory alignment with high-performance envelope standards.

Table 5. Proposed Phased Regulatory Integration Framework for Thermal Bridge Assessment.

Implementation Phase	Timeline	Key Actions	Compliance Level
Phase 1: Awareness	Years 1-2	Training, catalogue development	Voluntary
Phase 2: Pilot	Years 3-4	Large projects, data collection	Incentivized
Phase 3: Transition	Years 5-6	All new construction	Partially mandatory
Phase 4: Full Integration	Years 7+	All buildings, retrofits	Mandatory

6.3. Alignment with Vision 2030 and Sustainability Goals

The building sector in Saudi Arabia consumes about 75% of total electrical energy, with unprecedented consumption growth driven by rapid population growth and urbanization. Vision 2030 commitments to promote energy efficiency and renewable energy technologies create an enabling environment for regulatory advancement. Research demonstrates that several green building concepts are crucial for design and operation in hot-dry regions, including thermal mass, daylight optimization, natural ventilation, cavity walls, double-glazing, and solar panels.

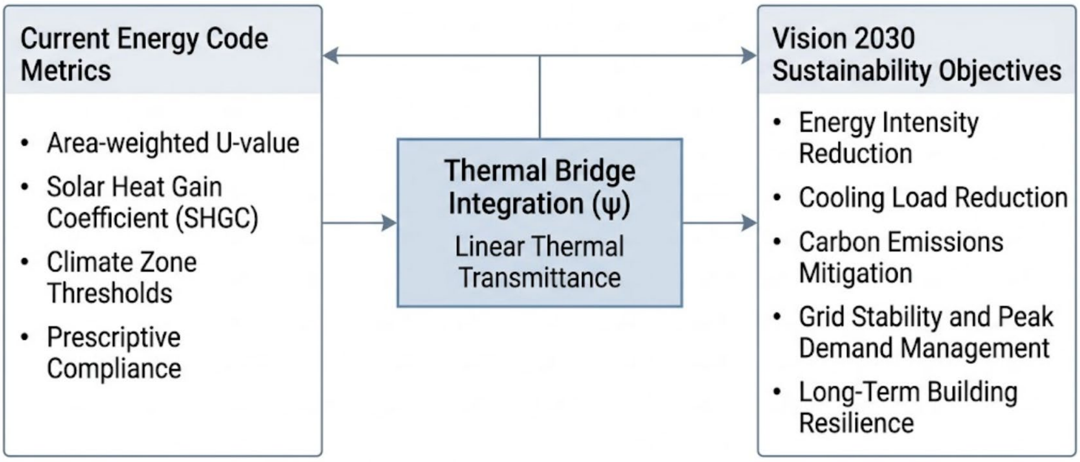

Figure 15. Alignment of fenestration regulation with national sustainability objectives.

Figure 15 conceptualizes the alignment pathway between current prescriptive energy code metrics and broader national sustainability objectives under Vision 2030. Integrating ψ-value assessment acts as a bridging mechanism between envelope-level physics and macro-scale energy policy goals.

Façade-integrated photovoltaic systems represent a technically viable and environmentally beneficial renewable energy solution aligned with Saudi Vision 2030 sustainability objectives. A 5.6

kWp BIPV façade system analysis demonstrates approximately 8,200 kWh annual electricity production, with ventilated façade configurations reducing temperature-related efficiency losses while contributing to reduced cooling demand and lower carbon emissions [45].

6.4. Study Limitations

This study relies on literature-based performance ranges and regulatory document analysis rather than empirical field measurements in Saudi buildings. Future research should validate ψ-related cooling impacts under monitored hot-arid operational conditions.

7. Conclusions and Recommendations

This comparative regulatory and analytical study identifies a significant regulatory blind spot in the assessment of fenestration thermal performance in cooling-dominated climates. Current energy codes, including the Saudi Building Code (SBC), ASHRAE 90.1, and IECC, primarily rely on area-weighted U-values and solar heat gain coefficients without explicitly integrating linear thermal transmittance (ψ) evaluation. Research consistently demonstrates that thermal bridges increase total building energy consumption by 5–30% and may elevate cooling loads by up to 25% in climate-sensitive façade configurations. The rapid expansion of sophisticated façade technologies in the GCC region amplifies the importance of addressing this regulatory gap. The combined regulatory comparison and analytical heat transfer modeling confirm that ψ omission produces amplified load effects under sustained high ΔT conditions typical of hot-arid climates.

Based on the literature synthesis, several recommendations emerge for regulatory advancement:

1. Adopt Explicit ψ-Value Requirements: Energy codes should incorporate mandatory thermal bridge assessment for fenestration systems, following established ISO standards and utilizing validated calculation methodologies.
2. Develop Regional Catalogs: Context-specific thermal bridge catalogs should be developed for common construction details in hot-arid climates, providing accessible compliance pathways for practitioners.
3. Implement Phased Integration: A graduated approach to regulatory implementation allows capacity building while progressively advancing compliance requirements toward mandatory performance-based assessment.
4. Support Technology Adoption: Incentive structures should encourage adoption of advanced fenestration technologies, including vacuum glazing, thermally broken frames, and optimized installation practices.

Future research should focus on developing climate-specific performance data for thermal bridge effects in hot-arid conditions, validating simulation methodologies against field measurements, and establishing economic models for regulatory compliance costs and benefits [46]. Additionally, investigation of emerging technologies, including AI-based thermal bridge analysis tools and advanced materials integration, offers opportunities for enhanced performance assessment approaches. The integration of computational modeling with local building codes, construction practices, and affordability constraints remains essential for successful implementation in developing economies [43].

As façade systems become increasingly complex in cooling-dominated economies, energy codes must evolve from prescriptive simplification toward multidimensional thermal accountability. Integrating ψ-value evaluation represents a necessary step in aligning regulatory architecture with physical reality.

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