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Review

Thermal Bridging in Windows: A Critical Review on Mitigation Strategies for Enhanced Building Energy Efficiency

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Abstract: Thermal bridging in windows presents a significant challenge for building energy efficiency, particularly at window-wall junctions where material transitions cause heat loss. As energy standards become more stringent, minimising these heat loss pathways is essential for achieving sustainable design objectives. Thermal bridges increase energy consumption, diminish insulation effectiveness, and compromise overall building performance. This review explores the impact of thermal bridges in windows and glazed areas, highlighting advancements such as thin-film photovoltaic (PV) glazing, vacuum glazing, aerogel glazing, low-e coated multilayer systems, transparent insulation materials (TIM), and phase change materials (PCM). It also evaluates high-performance window frame materials, such as fibreglass and composites, alongside advanced installation techniques like thermal breaks and insulation barriers at window-wall interfaces, for their ability to reduce thermal conductivity and heat transfer. Research indicates that thermal bridges increase building energy consumption by 5%-30%. Cutting-edge technologies, such as vacuum glazing with U values as low as 0.2 W/(m^2·K) and aerogel-filled frame cavities that reduce thermal permeability by 45%, demonstrate considerable energy-saving potential. Furthermore, precise installation techniques lower linear thermal transmittance (LTT) by up to 80%. A holistic approach that integrates advanced glazing technologies, optimised frame materials, and meticulous installation methods offers a powerful solution for enhancing window thermal efficiency, making a substantial contribution to the sustainable transformation of the built environment.

***Keywords*:** thermal bridging, window and glazed areas, glazing technologies, heat loss mitigation, thermal transmittance, insulation barriers

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1. Introduction

To enhance energy efficiency in buildings, there has been a significant shift towards constructing more tightly sealed and insulated structures. However, energy losses due to thermal bridges continue to emerge as a major issue, undermining the efforts to improve thermal insulation and energy conservation in the building environment [1]. Thermal bridges, which are areas where heat flows more readily due to a lack of continuity in insulation, are especially prevalent in locations where materials with differing thermal conductivity coefficients come into contact [2]. One such critical area is the junction between windows and walls. At these points, the transition between materials of varying thermal properties creates paths for heat to escape, contributing to overall energy loss [3]. Thermal bridges significantly influence the insulation performance of building envelopes, undermining overall energy efficiency. Research shows that they account for approximately 40% of the total heat loss through windows [4]. This substantial figure highlights the extent to which energy loss occurs even in well-insulated structures. Figure 1 illustrates the critical connections between building elements such as window-wall, door-wall, or wall-wall junctions that are susceptible to the thermal bridge phenomenon. These areas are significant because, despite the insulation of the surrounding building structure, uninsulated junctions can lead to substantial heat loss due to high heat transfer. The figure aims to emphasise the importance of recognising these potential energy loss points, from the glass and frame junctions to door and windowsills. This visual representation supports the idea that even small, uninsulated areas contribute to energy consumption and should be carefully considered in building design and retrofitting [5, 6]. Furthermore, the effectiveness of insulation around window frames is not only dependent on the quality of materials used but also on the skill of the installer [7]. Variability in installation quality can lead to inconsistent insulation performance, with substandard workmanship exacerbating energy losses significantly. Consequently, the presence of thermal bridges not only undermines the energy efficiency of otherwise well-designed buildings but also points to the need for rising attention to both material selection and construction practices to minimise these losses. Addressing these thermal inefficiencies could make a notable difference in achieving sustainable energy goals within the building sector [8].

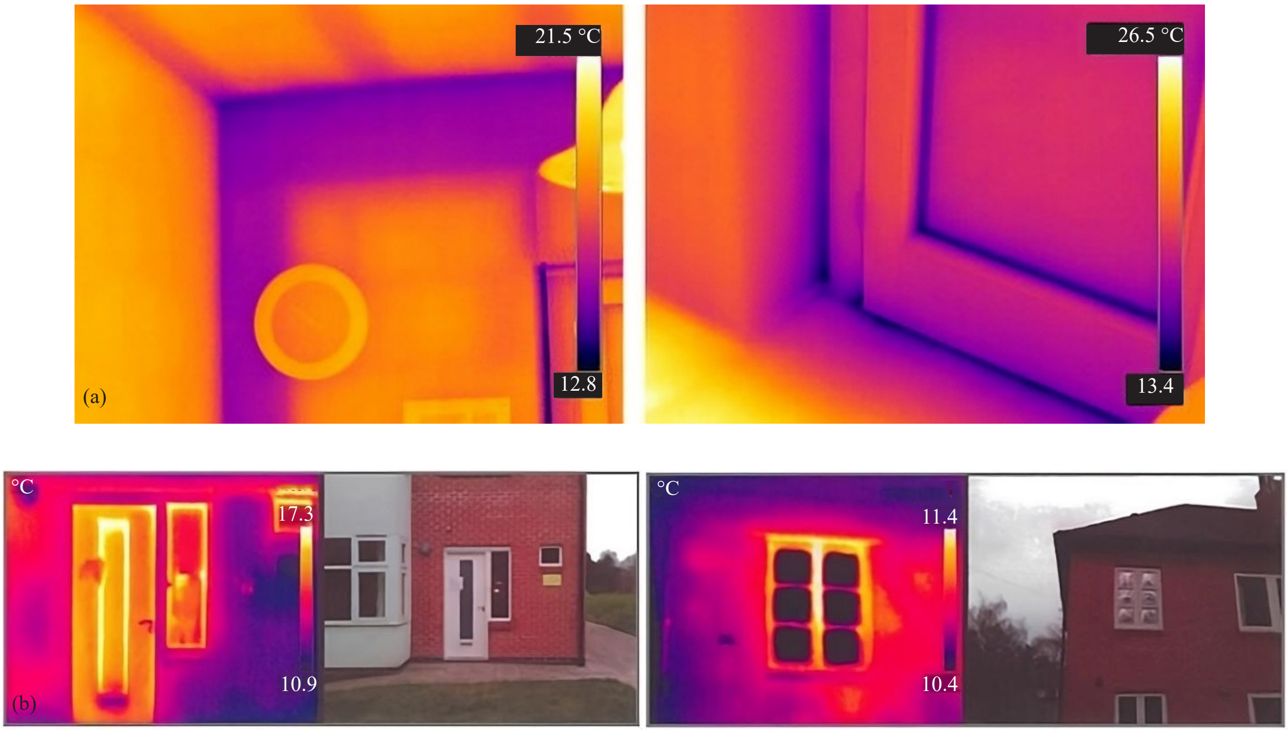

Figure 1. a) Demonstration of thermal bridging in the structure and window interface, specifically at the connection between the glass and frame [5], b) Thermal image of the south wall and window with reflective coil (right) as well as the front door and side window panel (left) [6]

Thermal bridges significantly degrade the thermal insulation performance of a building, impacting its overall energy balance [9, 10]. It is not only the thermal transmittance coefficient of the glazing that must be considered, but also factors such as the positioning of window frames, jamb insulation methods, and techniques for sealing window reveals, all of which play crucial roles in mitigating heat transfer [11]. Typically, thermal bridges form at structural joints or at points where different materials meet, weakening the overall capacity of the building envelope to act as an effective barrier against heat flow [12]. Beyond simply facilitating energy loss, thermal bridges can also create conditions that lead to issues such as condensation, mould growth, and unpleasant odours within interior spaces [13]. Particularly in glazed areas and window systems, thermal bridges act as heat loss pathways that diminish energy performance. This is largely influenced by the combined properties of the window glass and frame structure, the specific design of frame connections, and the quality of insulating materials used in these assemblies [14, 15]. For instance, windows with improperly sealed frames or lower-quality materials at contact points may allow increased heat flow, even if the glass itself is of high thermal resistance. To combat these losses, it is essential to improve the insulating properties of both the glazing and framing components. In aluminium-framed windows, for example, adding a polyurethane foam between the exterior and interior profiles has been shown to enhance thermal resistance, helping to reduce unwanted heat transmission across the frame [16]. This kind of strategic enhancement in insulation, applied not only to windows but also to other critical points where thermal bridges commonly occur, could contribute significantly to the energy efficiency of buildings. As construction standards increasingly emphasise sustainability, addressing thermal bridge mitigation through advanced materials and enhanced installation techniques becomes indispensable. By minimising these areas of thermal weakness, buildings can achieve a more stable indoor environment, reduced heating and cooling demands, and, ultimately, a lower environmental footprint [17].

Considering the overall energy consumption of buildings, improvements made to glazing surfaces can contribute significantly to reducing energy loss [18]. Research indicates that advancements in window glazing alone may reduce total energy loss by up to 10-25%, which is comparable to the effects achieved by increasing insulation thickness or installing high-performance windows with stringent standards [19]. In recent years, the transition from single-pane to double-pane glass, as well as innovations like solar photovoltaic (PV) vacuum glass, PV-integrated glass and colour-varying glass, have enabled thermal transmittance for glass to reach as low as 0.5 $W/(m^2 \cdot K)$. Despite these improvements, the thermal transmittance values for traditional window frames still remain above 1.0 $W/(m^2 \cdot K)$ for single and double-layered glass, while this value may drop below 1.0 $W/(m^2 \cdot K)$ with the increase of layers, suggesting substantial untapped potential for energy savings in this area [20-23].

The extent and impact of thermal bridges vary depending on several factors, including building type, structural design, climatic conditions, insulation level, and the specific structural solution used to manage thermal bridging [24]. According to European Standards in EN ISO 14683, a set of example cases is provided for different types of thermal bridges, with catalogues offering values derived from two-dimensional analyses. However, certain point thermal bridges (e.g., thermally conductive materials at connection points) often need to be included in these calculations, despite their potential to contribute to energy loss significantly [11]. Specific points of thermal bridging, such as those at window-wall interfaces, often emerge as critical factors in the energy profile of a building if overlooked [25]. It is, therefore, essential to account for these losses when calculating the total energy efficiency of a building. The careful alignment of insulation layers with the window frame plays a crucial role in preventing the formation of thermal bridges. However, practical considerations, such as water drainage requirements, frequently necessitate the use of metal exterior sills that can act as conductors, forming thermal bridges at these critical points. This makes the perimeter around window installations a particularly vulnerable area in the building envelope. To mitigate these effects, advanced installation techniques and materials are increasingly adopted, aiming to integrate both effective insulation and moisture control without compromising structural stability. Solutions such as thermally broken sill plates and insulated frame covers are being explored to minimise thermal losses. By systematically addressing these details, building designers can significantly enhance the energy performance of windows and, consequently, the overall thermal integrity of the structure.

In summary, improving the thermal insulation performance of window frames, ensuring high installation quality, and taking preventive measures against thermal bridges play a crucial role in enhancing building energy efficiency. These measures are essential, as thermal bridges can significantly increase energy demands and hinder progress towards sustainability targets. Therefore, they should be carefully assessed to maximise energy savings and reduce emissions effectively [26]. Addressing these aspects requires a detailed understanding of material properties, structural design, and the interaction of each element within the building envelope. Comprehensive evaluations of thermal bridge contributions, particularly around window installations, enable targeted interventions that minimise heat loss without compromising structural stability. For instance, utilising materials with optimised thermal conductivity in frame design, alongside advanced mounting techniques, ensures a more seamless insulation layer, reducing the risk of weak points in thermal performance. Furthermore, continuous advancements in thermal modelling now allow for more precise analysis of both linear and point thermal bridges, enabling architects and engineers to foresee potential energy inefficiencies and adapt designs accordingly. Ultimately, achieving high energy efficiency standards in buildings depends on an integrative approach, where each component-windows, frames, insulation, and structural details-works cohesively to form a robust barrier against energy loss.

In light of the increasing demand for energy-efficient and sustainable building designs, the mitigation of thermal bridges has emerged as a critical priority, particularly at window-wall interfaces. By addressing thermal bridging with advanced materials and innovative techniques, this review study underscores the substantial energy savings and environmental benefits achievable through these interventions. As evidenced by recent advancements, integrating state-of-the-art glazing technologies such as PCM glazing, TIM glazing, aerogel glazing, vacuum glazing, low-e coated gas and liquid filled multilayer glazing, and thin film PV glazing, alongside highly insulated composite frames, offers a dual benefit of enhanced thermal performance and reduced greenhouse gas emissions. Furthermore, precise installation practices, including the use of thermal breaks and optimised insulation at critical junctions, play a pivotal role in achieving near-zero energy buildings. This study aims to bridge the knowledge gap in the field, providing a detailed synthesis of emerging technologies and practical strategies for reducing thermal transmittance. These findings serve as a valuable resource for architects, engineers, and policymakers dedicated to advancing energy-efficient construction practices.

2. Literature review

Table 1. Overview of studies (2002-2024) on thermal bridge effects in window systems, based on window positioning, frame materials, and glazing systems

The goal of the study	Method	Main outcomes	Ref.
A new structural proposal is developed to enhance the thermal performance of historic buildings without compromising their architectural integrity, specifically focusing on the junction between the exterior window and wall. This design aims to mitigate the thermal bridge effect between the window frame and the wall, facilitating the usage of additional insulation materials.	The proposed structure is compared with four common window-wall junction designs, and its thermal performance is analysed.	• The new window-wall junction structure demonstrates superior thermal performance compared to other designs, particularly during the winter months, featuring a 42.4% reduction in surface heat flow and a shorter condensation formation time. • Additionally, a special coating applied to the window frame further reduces heat transfer.	[27]
Rising the surface temperatures of the window glass and connection points in wooden-framed double-glazed windows prevents condensation and mould formation.	A conductive rod and heating resistance wire are utilized to raise critical surface temperatures, which are then evaluated under specific boundary conditions through steady-state thermal analysis. This process is followed by a flow analysis that includes a radiator within the room. Finally, the results are verified using a thermal imaging camera.	• The presence of the rod increases the surface temperature on the windowsill and sides, distributing the heat evenly across the surface. • In the window detail with the rod, cold areas with a 12 °C isotherm are observed to be less visible. • The 5 W/m heating resistance wire, when combined with the rod, spreads heat over a wider area, preventing local overheating and making the temperature distribution more uniform.	[28]

Table 1. (cont.)

The goal of the study	Method	Main outcomes	Ref.
To analyse the energy performance of Polyvinyl Chloride (PVC) window frames with enhanced metal stiffening profiles, aimed at reducing deformation and air leakage.	Numerical and experimental analyses are conducted, with rigidification of PVC window frames achieved through the use of enclosed metal profiles. Additionally, frame cavities are filled with thermal insulation material to enhance performance.	• A 10% reduction in thermal conductivity is achieved by adding thermal insulation. • The effect of linear thermal bridging at frame-wall junctions is diminished. • Compared to the uninsulated frame, the LTT coefficient is mitigated by 9.7% at the windowsill, 1.2% at the jamb, and 3.6% at the lintel.	[29]
Demonstrate the benefits of enhancing energy efficiency through proper window installation and its integration with external walls.	An assessment of heating and cooling energy usage is conducted for the selected buildings, accompanied by thermal and moisture analyses using the TRISCO program. Additionally, the economic analysis is performed using the Audytor OZC.	• The correct installation of the thermal insulation layer in the windows reduces the annual heating demand by an average of 10%. • The proper selection of materials for both the load-bearing layer and the insulation layer significantly reduces heat losses, thereby enhancing the energy efficiency of buildings. • The suitable choice between the window installation system and the structural material of the external wall lowers energy costs. • The analyses focus solely on one window installation method, with plans for further analysis of alternative methods and materials in the future.	[30]
Investigating the impact of vacuum insulation panels (VIPs) on internal volumes in engineering applications.	Using numerical and experimental methods, five different internal volume shapes are examined: circular, equilateral triangle, square, regular pentagon, and regular hexagon.	• VIPs with circular volumes exhibit the lowest effective thermal conductivity (LETC) and thermal bridging effects. • In volumes with the same perimeter, circular volumes have the LETC and thermal bridging impacts, whilst hexagonal volumes have the highest. • In volumes with the same area, circular VIPs possess the LETC and thermal bridging effects.	[31]
Assessing thermal performance using on-site infrared (IR) thermography to evaluate thermal bridges and insulation defects at window-wall junctions.	The study examines surface temperature distribution for different test sites using simulation models to evaluate heat loss in window-wall junctions with high thermal mass.	• At Site A, the temperature difference between the interior and exterior is measured at 14.19 °C at time point 1 and 20.60 °C at time point 2. These differences provide critical indicators for the energy efficiency and heat loss of the buildings. • The lowest temperature readings are found nearest to the window-wall junction, suggesting the existence of thermal bridges, while temperatures rise as the distance from the junction increases.	[32]
Assessing the thermal bridging effect of the wooden window installation position in relation to wall thickness.	The thermal performance of windows has been modelled using various wall compositions at different window positions.	• The ideal position for window installation has been determined to be 7-11% of the wall thickness.	[33]
Examining the thermal conductivity between the frame system and structural elements in a traditional house and assessing the effectiveness of the insulation barrier.	An experimental study involving the installation of insulation layers with various frames (solid wood, aluminium, PVC, etc.).	• The use of a wooden frame instead of an aluminium frame with the insulation barrier gives rise to a significant enhancement in temperature values, increasing from 4.1 °C to 15.1 °C. • It is observed that the insulation barrier increases the distance between the frame and the floor temperature by 20 °C. • The use of the insulation barrier significantly reduces energy loss, decreasing it from 1,250 W/(m^2·K) o 770 W/(m^2·K).	[34]
Analyse the effects of the Light Steel Frame (LSF) wall structure on thermal bridging and energy performance.	The thermal bridging effects of the LSF structure are analysed using numerical methods with COMSOL Multiphysics, followed by an analysis of the application of thermal insulation to the steel frame to reduce thermal bridging.	• Steel bars contribute to heat losses by increasing the U value by between 28.4% and 41.6%. • Insulation applied to the exterior of the steel frame minimises thermal bridging effects and reduces heat loss.	[35]

Table 1. (cont.)

The goal of the study	Method	Main outcomes	Ref.
Evaluation of thermal bridges in high-performance window installations and comparison of different installation methods.	The window frame is mounted to the thermal insulation layer, employing 2D and 3D thermal bridge calculation methods.	• When metal connection elements are not taken into consideration, the thermal bridge value at the wall-window frame junction decreases by 80%. • A difference of 68% is observed between the thermal bridge values obtained from the 2D and 3D calculation methods.	[12]
Optimising thermal performance by adding radiant insulation panels (RAIPs) to broken-bridge aluminium window frames.	Thermal performance analyses are conducted using the finite element simulation method with THERM software.	• The addition of RAIPs to the frame cavity may decrease the thermal transmittance of the window frame by 7.43%. • The RAIP-type window frame offers low cost and high energy savings potential. • The RAIP should be placed in the centre of the frame and should be as thin as possible.	[16]
To examine the effect of fasteners in window assembly interfaces on thermal bridging, particularly when installed on thermal insulating material.	Analytical methods based on EN ISO 10211:2017 standard and numerical models.	• Suggesting minimum installation distance of 100 mm for windows directly mounted on thermal insulation. • Consideration of fasteners shows an increase in thermal transmittance, particularly at installation distances near the masonry layer. • The lowest LTT value observed is 0.026 W/(m^2·K) when installed centrally in insulation.	[36]
Enhance thermal conductivity performance and reduce thermal permeability of PVC window frames by adding aerogel granules to their internal cavities.	Aerogel granules are placed within the frame cavities, after which hot box tests and numerical modelling are performed. The distribution of aerogel and the edge effects are then analysed using IR imaging.	• Filling the PVC frame cavities with aerogel reduces the thermal permeability of the frame by up to 30%, and this value can be increased to as much as 45%. • Incorporating aerogel into the frame cavities reduces the U value of the frame to 0.80 W/(m^2·K).	[37]
Quantifying the thermal performance properties of vacuum glazing, focusing specifically on the heat flow and thermal transmittance around the edge of the glazing in different frame materials.	A 2D numerical calculation is performed using the THERM program to evaluate frames with specific thermal characteristics.	• The LTT for the edge of vacuum glazing is calculated as follows: Ψ = 0.023 W/(m·K) for wooden frames and Ψ = 0.036 W/(m·K) for wooden aluminium frames. • These values highlight the influence of frame materials on the thermal efficiency of vacuum glazing systems.	[38]
To enhance the thermal performance of aluminium window frames without changing their geometry by exploring different materials and cavity-filling strategies to reduce thermal transmittance and energy loss.	Computational Fluid Dynamics (CFD) in ANSYS FLUENT model aluminium window frames with two enhancement approaches: i) modifying the materials of the gasket and thermal barriers, and ii) filling the internal air spaces with polyurethane foam. The thermophysical characteristics of the materials and ambient conditions remain consistent, while the thermal conductivity of materials varies to examine its impact on the U value.	• Low-conductivity thermal breaks and gaskets greatly enhance thermal efficiency, achieving U value reductions of up to 6.67% for thermal breaks and 2.78% for gaskets. • Filling air gaps with polyurethane foam yields a 29.44% decrease in thermal transmittance. These results emphasise the critical role of choosing low-conductivity materials for window frames.	[39]
Scrutinising the thermal properties of window-wall connections to identify the most efficient window positioning that minimises the thermal bridge effect at the junction.	Thermal simulations are conducted on two windows with varying insulation properties and five different wall structures. For each wall type, a thorough analysis of the sill, head, and side components is performed to ascertain the most effective window positions. To quantify the thermal bridge effect, LTT values are calculated.	• The position of the window plays a significant role in the thermal bridge effect. The study reveals that depending on the window positions examined, LTT values decrease by up to 50%. • Windows with lower insulation properties exhibit lower LTT values compared to their highly insulated counterparts, indicating that the significance of the thermal bridge effect increases in better-insulated products. • However, the window position has minimal impact on internal surface temperatures, resulting in a maximum difference of only 0.5 K.	[40]

Table 1. (cont.)

The goal of the study	Method	Main outcomes	Ref.
To evaluate heat and moisture conditions at the window-wall interface and assess the impact of different installation methods on thermal insulation and microclimatic conditions.	Utilisation of CFD simulations to model various window installations and their interactions with wall construction, including partitions with and without insulation.	• Identified the optimal placement of windows within the insulation layer as the most effective installation method, along with the benefits of using aerogel mats and expanding tapes to reduce linear heat transfer coefficients. • Improved insulation and correct placement are crucial for condensation prevention and energy efficiency.	[41]
To assess the U value of argon-filled double-pane windows and to investigate differences between stated and actual U values.	Theoretical calculations, CFD analysis, and experimental testing in an environmental chamber to assess the U value at different points of the window sample.	• The U value from CFD analysis stands at 0.89 $W/(m^2{\cdot}K)$, closely matching theoretical data of 0.80 $W/(m^2{\cdot}K)$. • Experimental testing, however, reveals higher U values at different points: 1.25, 1.18, and 1.32 $W/(m^2{\cdot}K)$ for the top, centre, and bottom, severally. • Thermal bridges and edge effects impact the actual U value performance. Hence, it is advised to use measured U values in building energy demand analyses for greater accuracy.	[42]
Evaluate the thermal performance of junction thermal bridges for windows installed in buildings, focusing on the impact of installation methods and positions.	Two types of windows are used in the analysis: a 4-track sliding window and a tilt-and-turn triple-glazed window. The Window 7.4 and THERM 7.4 software are utilised for the assessment.	• Thermal loss due to junction thermal bridges decreases as window area increases, gradually levelling off as the area expands. • The linear thermal conductivity of the 4-track sliding window varies by more than 2.2 times based on the mounting method and placement. • For the tilt-and-turn window, thermal conductivity changes by over 7.7 times.	[43]
Accurately predict heat transfer through window frames under varying film coefficients to reduce thermal bridging caused by window frames in the design of energy-efficient buildings.	The traditional one-dimensional frame conductivity model is examined, and an alternative model that accounts for the non-planar morphology of the frame is proposed. The proposed model is compared with results obtained from THERM.	• An alternative model is suggested that considers the non-planar structure of frames and demonstrates a strong correlation with 2D simulation outcomes; the conventional model is appropriate for frames with thermal transmittance lower than 5 $W/(m^2{\cdot}K)$, whilst frames with U factors exceeding 6.2 $W/(m^2{\cdot}K)$ necessitate the alternative model for precise heat transfer depiction.	[44]
To provide design recommendations for LSF elements to improve thermal efficiency by addressing thermal bridges resulting from the high conductivity of steel in lightweight structures.	A parametric study using Finite Element Model to evaluate the effectiveness of various design changes (e.g., thermal break strips, slotted steel profiles, and insulation layer adjustments) on thermal performance.	• Implementing thermal bridge mitigation strategies results in an 8.3% reduction in the U value compared to the reference model. • Optimising insulation layers with contemporary materials like aerogel and VIPs leads to a 68% U value reduction. • Additional design guidelines include ensuring continuous insulation and selecting steel profiles with narrow slots.	[45]
Analysing the impact of thermal bridging in monolithic silica aerogel-insulated French-style windows and determining the optimal spacer and window frame system to enhance the performance of the window system.	A 3D finite element heat transfer analysis is conducted using COMSOL Multiphysics, employing aluminium, stainless steel, and PVC materials for the spacers.	• The PVC-framed window system performs best, achieving a U value of 0.92 $W/(m^2{\cdot}K)$. The type of window frame and the material of the spacer improve the U value by between 0.3% and 6.5%. • The vinyl-framed window system, structured with a PVC 'T' spacer and 'U' edge piece, achieves the best performance.	[46]
Investigating the energy load of thermal bridges formed where windows are offset from the external walls.	A contemporary insulation covering has been introduced, with 2D heat transfer effects taken into account. Simultaneous simulations are conducted using MATLAB and EnergyPlus to enhance accuracy in the analysis.	• It is established that the thermal bridges formed by the offset windows comprise 2-8% of the total house load. • The application of 1 cm and 2 cm of insulation reduces the energy load from thermal bridges by approximately 36-50%. • In cases where the external walls lack internal insulation, the energy load from thermal bridges created by offset windows accounts for 4-8% of the total house load, while in the case of 5 cm of internal insulation, this figure is 2-5%.	[47]

Table 1. (cont.)

The goal of the study	Method	Main outcomes	Ref.
Compare the calculation methods for thermal bridges at the window edges in building envelopes.	A 2D dynamic simulation method is utilised, ensuring compliance with the standards outlined in the article.	• It has been found that conventional window systems create significant thermal bridges, which must be considered in building design. Observations indicate that improperly calculated thermal loss rates can vary by up to 55%.	[48]
Investigate different solutions for window-to-wall connections and their impact on thermal performance, aiming to reduce thermal bridging effects in building envelopes.	THERM 6.3 software for various window-to-wall connection configurations.	• The optimal position for minimising heat loss is about 35 mm from the outer wind barrier to the window frame. • Increasing wall thickness generally raises thermal bridging, except when windows are positioned close to the interior. • Alternative framing designs can reduce thermal transmittance by up to 87%.	[49]
Analyse the thermal-bridging effects of operating hardware in casement-style window frames to assess its impact on the overall thermal performance of window frames.	Finite volume computational fluid dynamics modelling is used.	• Operating hardware can significantly impact the thermal performance of window frames, particularly in high-performance windows. • The thermal effect of hardware is influenced by factors like fastener types, hardware location, and penetration depth. • Base performance level and frame material alone do not determine the thermal impact of hardware, as design differences play a major role.	[50]
Analysis of thermal bridges affecting the energy performance of windows and evaluation of the impact of frame installation.	The THERM 5.2 software is utilised to calculate thermal transmission values in accordance with the EN ISO 10211:2007 standard. Various frame positions and window aperture insulation configurations are examined to assess their impact.	• It is seen that shifting the window from the inside to the outside decreases linear thermal conductivity by 70-75%. • It has been determined that the frame position (external, internal, and intermediate) and window aperture insulation configuration significantly impact the overall thermal performance of the windows.	[51]
Develop an energy-efficient window frame using glass fibre reinforced polyester (GFRP) material, comparing its energy and structural performance with wooden and aluminium frames.	Rational product development method with detailed thermal calculations and structural analysis.	• GFRP frames have a lower U value, increase solar gain, improve indoor comfort, and meet future energy standards. • The GFRP window frame shows significantly lower heating demand in a reference office building than other frame types. • The window frame, whose width is reduced by 12 mm with a special hinge mechanism, provides annual energy savings of 6.5 kWh/m^2.	[52]
Minimise thermal bridging through typical window systems in buildings located in hot regions, ensuring efficient design.	An integrated 3D dynamic simulation approach is utilised to evaluate thermal bridges, demonstrating reliability and applicability across various geometric shapes.	• The edge insulation approach is found to be the most effective for reducing thermal bridging, resulting in lower cooling loads. • Other modifications (internal insulation, insulated edge, resistive marble, window indentation) also contribute to decreased thermal bridging, with edge insulation being the most attractive option.	[53]

Table 1 provides a comprehensive summary of studies (2002-2024) addressing thermal bridge effects in window systems. The table highlights the critical role of window positioning, frame materials, and glazing systems in mitigating thermal bridging. As building design shifts towards low and zero carbon goals, the U values of building components are optimised to minimise heat loss. However, the U values of windows remain relatively high, allowing heat to transfer easily through the window systems, which are susceptible to thermal bridging. This phenomenon emphasises the importance of addressing thermal bridges in the transition to low and zero carbon technologies by 2030-2050. The table discusses advanced glazing technologies as key strategies for reducing thermal bridging and improving the energy efficiency of window systems. Researches indicate that the installation locations of windows and the types of materials used play a significant role in building energy efficiency. Specifically, it is observed that the proper placement of windows and their integration with thermal insulation materials can reduce annual heating demand by an average of 10% [29]. Furthermore, the usage of various window frame types proves effective in lowering thermal transmittance coefficients. Studies show that the thermal bridging effect is also related to how far the windows are positioned from the exterior walls, contributing to 2-8% of the total heat load in a home [47]. Consequently, it is essential to optimise the positioning of windows, the choice of frame materials, and insulation methods. The table summarises the effects of thermal bridges arising from windows on building energy efficiency and emphasises their role in energy consumption. Energy consumption in the current construction environment poses a significant challenge, and solutions to address these issues are increasingly being explored. However, there is a need for specialised efforts to prevent the formation of heat bridges at windows and junctions. Thermal bridges often result from improper operation, flawed planning, inappropriate material selection, or incompatible materials. In this context, it is crucial for engineers and architects to be diligent in their material choices and building designs. Particularly, employing suitable sealing and insulation techniques during window installation is critical to minimising thermal bridging. Moreover, future research should enhance investigations into window systems and junction details, as well as develop new materials and installation methods. Additionally, strategies that focus on positioning window frames, insulation applications, and the use of modern building materials are important for reducing the impact of thermal bridges on building design. This approach will enable a reduction in energy costs and improve the overall energy performance of buildings. Furthermore, to promote energy savings, it is vital to organise training programmes that raise awareness among construction sector professionals regarding thermal bridges and energy efficiency.

In accordance with the studies presented in the literature table, various methods are evaluated to reduce each occurrence of thermal bridging. Analyses of these methods' pros and cons can shed light on efforts to enhance the energy efficiency of window frames. For instance, applications like metal reinforcement profiles emerge as robust solutions to increase the durability of frames and reduce long-term deformation risks. However, due to metal's high thermal conductivity, a highly attentive insulation strategy is necessary to prevent energy losses; otherwise, metal reinforcements risk forming potential thermal bridges, which could reduce system efficiency rather than enhance it. In addition, insulation materials used within frame cavities significantly improve energy efficiency. These low thermal conductivity materials not only limit heat loss but also contribute to more comfortable indoor conditions. Yet, the performance of insulation materials varies depending on the type used and proper application, which once again highlights the importance of high standards in workmanship and project oversight in construction. Furthermore, decision-makers must carefully consider the cost of insulation materials, particularly those with high performance. Aerogel, considered an innovative option, stands out for its low thermal conductivity and delivers exceptional insulation when utilised within frame cavities. Nevertheless, aerogel is relatively high cost and challenging application requirements remain primary factors limiting its widespread use. However, in the right locations and projects, aerogel makes it possible to achieve levels of energy performance that traditional insulation materials cannot provide. Moreover, the identification and design strategies to mitigate thermal bridges caused by structural elements, such as lightweight steel frames, markedly enhance the overall building's energy performance. Yet, these improvements typically entail additional engineering and material costs, which can complicate applicability in projects with budget constraints. Even so, such measures contribute to environmental sustainability by reducing long-term energy consumption. In conclusion, various improvement methods applied to window frames indicate that optimal solutions should be carefully assessed for each project. Solutions aligned with project requirements, budget constraints, and targeted energy efficiency goals are most likely to provide maximum benefits in terms of energy savings and long-term performance.

3. Thermal bridge mitigation for window applications

Thermal bridges, or areas in a building envelope that conduct heat at a higher rate than surrounding materials, significantly impact the energy efficiency of buildings. Windows, which are essential components of the building envelope, are particularly prone to thermal bridging due to the materials used in their frames and glazing systems. When designing energy-efficient buildings, addressing these thermal bridges to minimise heat loss and enhance indoor comfort is crucial. Conventional glazing systems highlight the challenges associated with thermal bridges in windows. For instance, uncoated single glass with a thickness of 6 mm has a U value of 5.70 W/(m^2·K), which indicates significantly high heat loss. On the other hand, double glazing systems offer improvements, with uncoated double glass featuring a 12 mm air cavity achieving a U value of 2.80 W/(m^2·K), whilst increasing the cavity to 15 mm reduces the U value further to 1.40 W/(m^2·K). The addition of argon gas in the cavity enhances thermal performance, with a U value of 1.20 W/(m^2·K). More advanced configurations, such as uncoated triple glass with a 16 mm argon-filled cavity, reduce the U value to 0.79 W/(m^2·K). Technologies like monolithic aerogel and granular aerogel in double glass systems demonstrate exceptional performance, with U values of 0.65 W/(m^2·K), and 0.44 W/(m^2·K), respectively [54]. These values underscore the necessity of advanced glazing solutions to mitigate the impact of thermal bridges effectively. This section explores several innovative strategies for mitigating thermal bridges in windows, including the use of vacuum glazing, vacuum PV glazing, thin-film coatings, and PCM glazing. Advanced glazing technologies significantly surpass the thermal performance of conventional systems by achieving lower U values, thereby minimising heat loss and enhancing indoor thermal comfort. Moreover, the usage of advanced glazing systems offers opportunities for energy generation and improved insulation. For buildings located in high-heat potential areas, these solutions not only address the challenges of thermal bridging but also contribute to overall energy efficiency. A key aspect of reducing the impact of thermal bridges in windows is to focus on improving the performance of glazing systems while considering both insulation and energy generation.

Vacuum glazing is one of the best ways to reduce thermal bridging. It creates a vacuum between two glass panes to minimise heat transfer. This method improves insulation without adding thickness, which is useful for buildings with limited space. Studies show that, with four low-e coatings and stainless steel support pillars, vacuum glazing can reach an overall heat transfer rate as low as 0.20 W/(m^2·K). Besides this, if the vacuum glazing is used alone, the overall heat transfer coefficients will become 0.40 W/(m^2·K) [55]. In comparison, uncoated double glazing with a 12 mm air cavity has a U value of 2.80 W/(m^2·K), indicating that vacuum glazing reduces the heat transfer rate by approximately 93% [54, 56]. This low U value helps cut energy use and greenhouse gas emissions, making vacuum glazing a good choice for energy-efficient windows. In climates with big temperature changes, vacuum glazing reduces heat loss in winter and limits heat gain in summer, keeping indoor spaces comfortable all year round. For instance, upgrading 25.6 million UK dwellings with vacuum glazing could lower carbon emissions by about 40 million tonnes for each year, which is a big step towards higher energy standards in buildings [56].

Building on the concept of vacuum glazing, vacuum PV glazing introduces a dual-functionality system that combines insulation with energy generation. By incorporating PV cells into the vacuum glazing structure, this technology allows windows to capture solar energy and convert it into electricity while providing superior thermal insulation. For instance, Tan et al. [57] develop a numerical heat transfer model for a four-layer CdTe-based vacuum PV glazing, incorporating dynamic power generation and validating it through experiments. The model shows that vacuum PV glazing achieves a U value of 0.89 W/(m^2·K), which aligns with experimental results, and provides considerable energy savings, with up to 64% reduction in heat loss during air conditioning seasons in cold climates. Furthermore, the vacuum PV glazing generates up to 48 kWh/m^2 annually, demonstrating its potential for zero-energy buildings and energy-efficient applications across various climate zones in China. Vacuum PV glazing is especially valuable for commercial buildings or residential properties with large, south-facing windows, where solar exposure is high. Not only does this technology reduce the overall energy consumption of a building, but it also allows buildings to generate renewable energy, making it an attractive solution for sustainable building practices. In cities where energy demands are high and there is ample sunlight, incorporating vacuum PV glazing can lead to significant long-term energy savings.

Another advanced glazing solution for thermal bridge mitigation is thin-film coating glazing, which involves applying a thin, transparent film to the surface of window glass. These coatings can reflect IR radiation, thereby reducing heat transfer through the window. Thin-film coatings are effective in controlling solar heat gain whilst maintaining high levels of visible light transmission, making them ideal for buildings where daylighting is a priority. They help to minimise the demand for mechanical cooling in the summer months by reflecting excess solar heat, thus enhancing overall energy efficiency. Thin-film glazing is particularly beneficial for large window areas in office buildings, where solar heat gain can lead to substantial cooling costs. Additionally, these coatings can be applied to existing windows during retrofitting projects, offering an affordable and effective method for improving the thermal performance of older buildings. Cuce et al. [58] comprehensively evaluate the potential of thin film coatings as a retrofit solution for conventional window systems, focusing on their ability to control ultraviolet (UV), visible light, and solar radiation. The study demonstrates that ceramic and metallic thin film coatings effectively block up to 93% of incoming light and nearly 100% of UV rays. Additionally, these coatings are highlighted for their thermal insulation properties, which enhance energy efficiency and adaptability to various climatic conditions.

Another promising solution for enhancing the thermal performance of windows is PCM glazing, which is commonly applied to double or multi-layered glass units due to the substantial advantages it offers. PCM glazing integrates materials that absorb or release heat as they undergo phase changes between solid and liquid states. These materials are embedded within the glazing layers in several ways. For instance, paraffin wax, a commonly used PCM, is integrated into the cavities between glass panes, where it remains in solid form until the surrounding temperature triggers its phase change. However, the durability of PCM glazing, particularly under varying environmental conditions, presents a significant consideration. The integrity of PCM, encapsulating materials, and sealing systems can be compromised over time due to factors such as repeated thermal cycles, UV exposure, and mechanical stresses from temperature fluctuations. This can affect the PCM's latent heat capacity and phase transition temperature, potentially diminishing its performance. Alternatively, microencapsulated PCM particles are dispersed within interlayer films or laminated resin layers, ensuring uniform distribution and stability without the risk of volumetric expansion. The phase change process is fundamental to the temperature regulation capabilities of PCM glazing. During the day, as the indoor temperature rises, the PCM absorbs heat and transitions from a solid to a liquid state, storing thermal energy in the form of latent heat. At night, when temperatures drop, the PCM releases this stored heat as it re-solidifies, helping to stabilise indoor temperatures and reducing reliance on heating, ventilation, and air conditioning (HVAC) systems. This cyclical process is particularly effective in climates with significant diurnal temperature variations. Temperature fluctuations can create stress between the PCM, encapsulating material, and glass layers due to differing expansion rates, potentially leading to cracks or leaks. Lacasse et al. [59] highlight that such stresses are amplified under climate change scenarios, further underlining the need for robust encapsulation and sealing solutions. Quantifying the performance of PCM glazing involves assessing key thermal properties, such as the melting range and heat storage capacity. Paraffin wax, a common type of PCM, is preferred due to its low cost. However, its low thermal conductivity and significant volume change during phase transition pose challenges that limit its applications in buildings [60]. PCM glazing can absorb substantial amounts of thermal energy without a significant rise in surface temperature, making it an effective solution for thermal management. Moreover, the durability and performance of PCM glazing can be impacted by environmental factors like UV radiation and humidity, which may degrade both the PCM material and the sealing systems over time, potentially leading to leaks and reduced functionality. Uribe and Vera [61] investigate the use of PCM glazing in office buildings located in environments with high solar radiation and substantial day-night temperature differences. Their year-long real-scale experiment in Santiago, Chile, reveals that PCM glazing significantly reduces transmitted solar radiation during phase transitions. Moreover, it achieves notable mitigations in HVAC energy consumption for heating and cooling-between 22% and 45%-when compared to traditional double-clear glazing. King et al. [62] aim to improve window performance by integrating PCM into a double-glazed window unit. Technical-grade paraffin is used as the PCM and tested within a 12 mm gap. It is found that the glass containing PCM allows sufficient light transmittance throughout the day. Furthermore, the use of PCM reduces indoor temperature fluctuations from 21 °C to 11 °C, lowers the inner glass temperature by 8.5 °C, and achieves a 3.76% reduction in energy consumption. However, long-term studies and improvements in encapsulation materials are crucial for ensuring that these benefits are maintained over time. On the other side, Celik et al. [63] examine the potential of graphene nanoplatelets to improve the thermal performance of microencapsulated PCMs for double-glazed window applications. Their study focuses on the energy storage and heat transfer characteristics of hybrid PCMs with graphene incorporated at mass ratios of 1% and 0.1%. Experimental findings reveal that adding 1% graphene nanoplatelets leads to a significant 10 °C increase in peak temperature compared to a control sample, although this enhancement comes with a 14% reduction in average light transmittance. The improved temperature response is attributed to the increased solar radiation absorption due to the dark colour of the graphene and its high thermal conductivity. By incorporating advanced PCM technologies with optimised latent heat capacities and phase transition temperatures tailored to specific climatic conditions, PCM glazing not only improves energy efficiency but also contributes to the sustainability of building designs, positioning it as a vital innovation for the future of energy-efficient architecture. However, the challenge remains to develop materials and design approaches that enhance the long-term durability of PCM glazing under variable environmental conditions, ensuring continued performance and reliability in the face of potential degradation mechanisms.

In addition to the use of advanced glazing technologies, addressing thermal bridging around the window frame is equally important. High-heat potential areas, such as kitchens or industrial environments, require particular attention to thermal bridge mitigation. In these areas, windows may be subjected to extreme temperature gradients, making it crucial to reduce thermal bridging effectively. One of the most straightforward solutions is using highly insulated window frames made from materials with low thermal conductivity, such as fibreglass or composite materials. These frames can significantly reduce the impact of thermal bridges by limiting heat transfer through the frame. Moreover, ensuring that the window-to-wall connection is properly sealed and insulated can prevent air leakage, which further enhances the window's thermal performance. For buildings located in regions with high solar exposure, integrating thermal break materials into the window frame, such as polyurethane or polystyrene foam, can reduce the effects of thermal bridging. These materials create a barrier that prevents heat from transferring between the inside and outside of the building. Additionally, designing the frame to reduce the width of the window profile can also help minimise heat loss. Narrower frames reduce the surface area through which heat can pass, thus improving the overall thermal performance of the window. When combined with advanced glazing systems like vacuum glazing or PCM glazing, these strategies can significantly enhance a building's energy efficiency.

It is important to recognise that no single solution is sufficient to eliminate thermal bridges entirely. Instead, a combination of advanced glazing technologies and well-designed window framing systems should be used to achieve optimal thermal performance. For example, pairing vacuum glazing with thin-film coatings or integrating PCM glazing with highly insulated frames can provide both thermal insulation and solar heat gain control. A holistic approach that considers the specific needs of the building, including its climate, energy requirements, and architectural design, will yield the best results. Furthermore, retrofitting existing buildings with these advanced technologies can be an effective way to improve energy efficiency without the need for full window replacements. Figure 2 is supported by visuals for each of the advanced glazing technologies mentioned above.

Figure 2. Advanced glazing technologies for mitigating thermal bridges, including a) vacuum glazing, b) vacuum PV glazing, c) low-e coating glazing, and d) PCM glazing in solid (left) and liquid (right) states [64]

Moreover, TIM glazing, and smart glazing represent innovative solutions for enhancing building energy performance. Transparent insulation materials (TIMs) have been integral to modern glazing systems since their introduction in the 1960s, striking a balance between thermal insulation and light transmission. By utilising advanced materials such as aerogels, structured polymers, glass or plastic capillaries, and honeycomb structures sandwiched between two glass panes, TIMs offer exceptional thermal performance while allowing natural light to penetrate [60]. These systems effectively diffuse light, significantly reducing glare and shadowing, which enhances daylighting and improves occupant comfort [65]. However, despite their benefits, a key drawback of TIM-filled windows is their limitation in providing a clear view to the outside, as noted by Robinson and Hutchins [66]. Smart glazing uses advanced technologies such as electrochromic, thermochromic, and photochromic coatings to dynamically adjust light transmission properties in response to changing external conditions. This adaptability enhances thermal comfort and energy efficiency by effectively regulating solar heat gain and glare, making it a versatile solution for modern energy-efficient buildings [67].

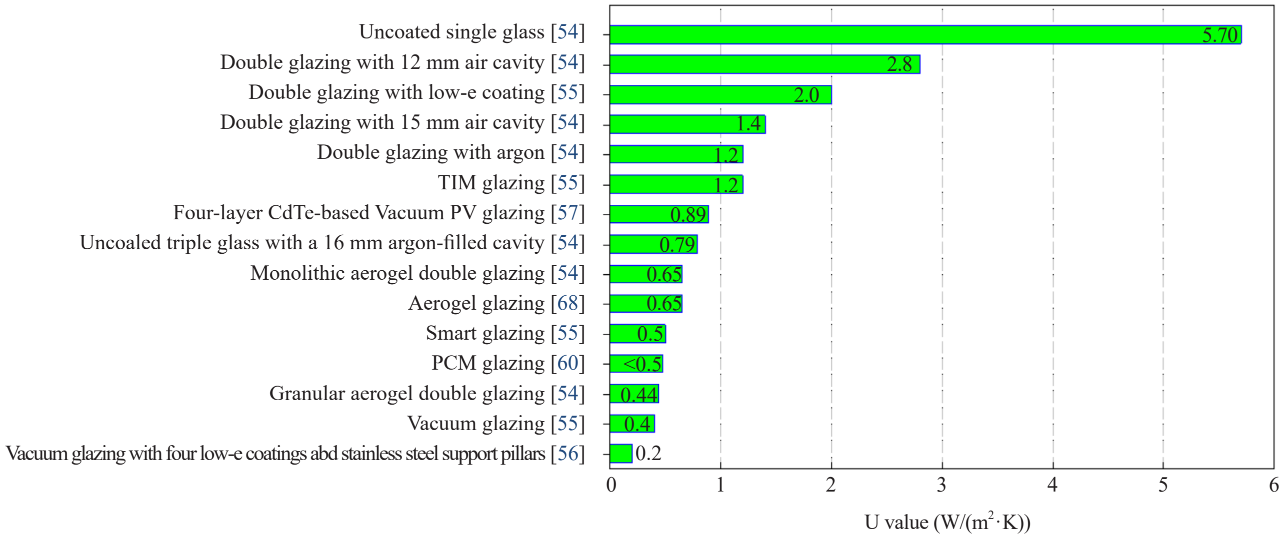

Figure 3. Comparative U values of traditional and advanced glazing systems [54-57, 60, 68]

Figure 3 presents a comparative analysis of U values across various traditional and advanced glazing systems. As expected, the highest U value is observed in the single glazed system at 5.70 W/(m^2·K) [54], while the lowest U value is achieved with vacuum glazing featuring four low-e coatings and stainless steel support pillars, which demonstrates an impressive thermal performance at 0.2 W/(m^2·K) [56]. When comparing these extremes, the substantial reduction in U value underscores the advancements in glazing technology. Notably, double glazing, which is among the most widely used systems, exhibits a U value of 2.8 W/(m^2·K) [54]. This represents a significant improvement compared to single glazing; however, it remains markedly higher than the vacuum glazing benchmark. Specifically, the U value reduction from 2.8 W/(m^2·K) to 0.2 W/(m^2·K) highlights an 92.86% decrease, showcasing the potential for advanced glazing systems to revolutionise thermal efficiency in building applications. Such advancements not only minimise thermal bridging but also align glazing performance with the stringent requirements of modern façade designs. This progression signifies a critical step towards eliminating thermal inefficiencies, paving the way for sustainable and energy-efficient building envelopes.

In conclusion, reducing thermal bridges in windows is an essential strategy for improving the energy efficiency of buildings. By incorporating advanced glazing technologies such as vacuum glazing, vacuum PV glazing, thin-film coatings, TIM glazing, smart glazing, and PCM glazing, and by using high-performance window frames, it is possible to significantly reduce heat loss and improve thermal comfort [69]. Novel window and glazing systems need to be selected depending on mainly climatic conditions, building type, thermal and acoustic expectations and cost [70].

Alternative facade and roof solutions like greenery surfaces [71] can be also a good strategy for a holistic retrofit case when considered along with the said novel window systems. These strategies not only contribute to energy savings but also enhance the sustainability of buildings. As the demand for energy-efficient buildings grows, the implementation of these thermal bridge mitigation strategies will play a crucial role in meeting modern energy standards and reducing the environmental impact of the building sector.

4. Conclusion

This mini review comprehensively explores the significant impact of thermal bridges in window systems on building energy efficiency, alongside strategies for their mitigation. Thermal bridges, particularly at window frame systems and window-wall junctions, reduce insulation effectiveness and elevate energy demands. Studies underline the role of frame materials in influencing thermal performance; materials with low thermal conductivity, such as fibreglass and composites, can effectively minimise heat transfer. Advanced technologies also offer innovative pathways for addressing thermal bridges. For instance, vacuum glazing, phase-change material (PCM) glazing, and thin-film coating glazing are recognised for their energy-saving potential and ability to enhance indoor comfort. Additionally, incorporating thermal barriers and proper insulation within window frame systems is essential to limit energy losses at critical junctions. When implemented effectively, these measures improve the thermal performance of window systems and contribute to the modernisation of building designs that comply with contemporary energy standards. Reducing the impact of thermal bridges requires employing low-conductivity frame materials, adopting advanced glazing technologies, and ensuring meticulous insulation at window-wall interfaces. These strategies are pivotal for optimising building energy efficiency and promoting sustainable architectural practices. Key findings of this review are summarised below:

• Thermal bridges can increase the overall energy consumption of buildings by 5% to 30% [26], making it crucial to eliminate these losses in line with the 2050 targets for zero-energy demand buildings. Modern architectural designs must address and eliminate these weak points to improve energy efficiency.

• Innovative solutions such as vacuum glazing can minimise heat transfer without increasing window thickness by providing high insulation with U values as low as 0.2 W/(m^2·K) with the addition of low-e coating [56]. However, when it is not added, the value is just 0.4 W/(m^2·K) [55].

• In regions with significant temperature differences, such as Scandinavian countries, building facades are designed with high thermal resistance. As a result, the windows tend to have high U values, leading to substantial heat losses and thermal bridging. To mitigate these issues, it is crucial to implement innovative solutions and ensure high resistance at the windows and their connection points. Aerogel-filled or vacuum glazing is highly recommended for such cold climates.

• In hot climates, thin-film coating technology helps control solar heat gain while allowing visible light to pass through, reducing energy consumption and enhancing daylight access. This contributes to meeting the sustainability requirements of modern buildings and supports the achievement of zero-energy demand targets.

• Uncoated double glazing, due to its high U values (e.g., 2.80 W/(m^2·K) and above) [54], has the potential to be replaced by higher-performance glazing systems in the future. This transition is crucial for meeting the energy performance standards required by modern building designs.

• Fibreglass and composite frames, with their low thermal conductivity, limit heat transfer and reduce the impact of thermal bridging. Frame designs incorporating thermal breaks enhance window performance and contribute to achieving zero-energy demand targets.

• Proper insulation and sealing at window-to-wall connections prevent heat loss whilst maintaining structural integrity, enhancing energy efficiency in modern architectural structures. Thermal barriers are an effective solution for reducing thermal bridging in these areas.

• PCM glazing absorbs and releases heat during temperature fluctuations, improving indoor comfort and reducing reliance on HVAC systems. This is particularly important for energy-efficient buildings of the future, especially in line with the 2050 targets.

• The distance between windows and exterior walls can account for 2% to 8% of the energy load [47]; proper positioning and insulation applications are effective in minimising these losses, aligning with zero-energy demand goals.

• Thin-film coatings provide a cost-effective solution in renovation projects for older buildings, enhancing the performance of existing windows without the need for complete replacement. This offers a critical advantage for modern building refurbishment strategies.

• Vacuum PV glazing, with its energy generation capabilities and low U values reaching 0.89 W/(m^2·K) [57], can enhance energy efficiency in regions with high solar radiation. However, it should be carefully planned for very hot climates and used in a way that aligns with the requirements of future zero-energy buildings.

• Further research should focus on developing cost-effective, scalable materials and techniques for both new constructions and retrofits, enabling widespread implementation of energy-efficient window systems across diverse building types. Enhanced modelling tools and real-world performance analyses will be vital in supporting the integration of these solutions into modern building codes and standards.

Conflict of interest

There is no conflict of interest among the authors.

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