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A Window into Scotland's Heritage: Evaluating the Role of Sash and Case Windows in Historic Preservation and Sustainability

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Abstract

This paper explores the intersection of heritage preservation and sustainable retrofitting through a thermal performance analysis of Scotland's iconic sash and case windows. Rooted in the country's architectural history, these windows are widely recognized for their aesthetic and cultural significance but face increasing scrutiny under modern energy efficiency standards. This study examines how retrofitting techniques, particularly the application of advanced vacuum glazing, can improve thermal performance without compromising the historic integrity. A positivist, quantitative approach was employed within a case study of a typical Scottish detached house to simulate and evaluate different window types against selected energy efficiency metrics. A Building Information Model (BIM) of the case study was developed in Autodesk Revit 2025, incorporating five window configurations: (1) original single-glazed sash; (2) new sash with double glazing; (3) new sash with vacuum glazing; (4) refurbished sash with vacuum glazing; and (5) a modern tilt-and-turn window. The BIM was populated with material and energy parameters, enabling annual simulations of energy use and heat transfer to evaluate each configuration. Energy simulations were conducted using the Autodesk Revit Insight 365 plugin, which assessed thermal performance by analysing annual energy use and heat transfer rates to evaluate the effectiveness of each glazing option. A comparative analysis was performed using u-values and annual thermal performance data. Results show that vacuum-glazed retrofits reduce heating demand by over 70%, achieving U-values consistent with modern regulation (1.4 W/m²K). However, these high-performance refurbishments slightly increased cooling needs due to reduced ventilation. The findings echo existing concerns about traditional single-glazed sash inefficiency while reinforcing the potential of smart retrofit solutions to reconcile heritage conservation with sustainability goals. Despite limitations such as modelling assumptions, limited variety, and climatic variability, this research provides a strong foundation for the future use of vacuum glazing in heritage windows. The results support retrofitting as a compelling strategy to reconcile the preservation of built cultural heritage with the urgent need to reduce carbon emissions in the built environment.

Keywords
Historic Preservation, Sustainability, Building Information Modelling, Case Study, Scotland Heritage

1. Introduction

Scotland's built environment is recognised globally for its architectural heritage. It reflects centuries of craftsmanship, innovation, and cultural identity. A defining feature of this heritage is the sash and case window, first introduced in the late 17th century (Guest, 2021). These windows can be seen across Georgian, Victorian, and Edwardian buildings throughout Scotland. Sash windows are integral to conservation areas and listed properties. They contribute not only to aesthetic value but also to the historical authenticity of Scottish towns and cities (Historic Scotland, 2008). However, their technical performance presents a growing challenge in the context of climate change and increasingly stringent energy regulations (Bülow-Hübe, 2001; Hilston, 2025). Original sash windows are typically constructed with single glazing and timber frames. They often exhibit U-values more than 5.0 W/m²K, which is far below the performance required by modern building standards of 1.4 W/m²K (Historic England, 2023). This results in considerable heat loss, higher energy consumption, and increased operational carbon emissions. Consequently, many historic windows have been replaced with modern alternatives such as uPVC double glazing (Hilston, 2025). While these replacements achieve improved thermal performance, they compromise the historic fabric, increase embodied carbon, and take away the authenticity of heritage buildings. Modern retrofitting practices like this not only risk the loss of cultural identity but also undermine sustainable principles in modern construction (Dixon, 2014). The strain between conservation and modernisation creates a pressing question: how can Scotland's sash and case windows be preserved while also contributing to national carbon-reduction goals? Existing retrofit strategies, such as secondary glazing, draught-proofing, and heavy curtains, have been shown to improve thermal comfort but often fail to meet regulatory standards or maintain heritage aesthetics (Fitton et al., 2017). However, the emergence of advanced glazing technologies, particularly vacuum glazing (VG), offers a promising solution. Vacuum glazing consists of two panes of glass separated by a micro-spacer and a cavity consisting of no gas, creating a vacuum environment that minimises heat transfer by conduction and convection. This allows it to achieve U-values as low as 0.4 W/m²K, with the thickness of a standard single-glazed unit making it especially suitable for heritage retrofits (Fineo, 2025). Vacuum glazing has the potential to upgrade historic windows to modern performance standards without compromising their visual integrity (Cuce & Cuce, 2016). This paper addresses the critical gap in evidence surrounding the performance of vacuum glazing in heritage contexts.

The study provides compelling evidence that retrofitting traditional sash windows with advanced glazing technologies can deliver both heritage preservation and sustainability benefits and argues that sash and case windows should not be viewed as obsolete but as assets that can contribute to sustainable futures for Scotland's built environment.

2. Methodology

This study adopts a positivist, quantitative methodology to evaluate the thermal performance of sash and case windows under different retrofit scenarios using a case study approach (Junjie & Yingxin, 2022). The study was developed using a Building Information Model of a typical Scottish three-bedroom detached house using Autodesk Revit 2025. The case study BIM model configured the living areas facing south to maximise solar gain, and all bedrooms were oriented north and west to simulate heat loss scenarios. This setup reflects common housing stock and ensures relevance to Scotland's climate to evaluate different window configurations. The case study model is presented in Figure 1.

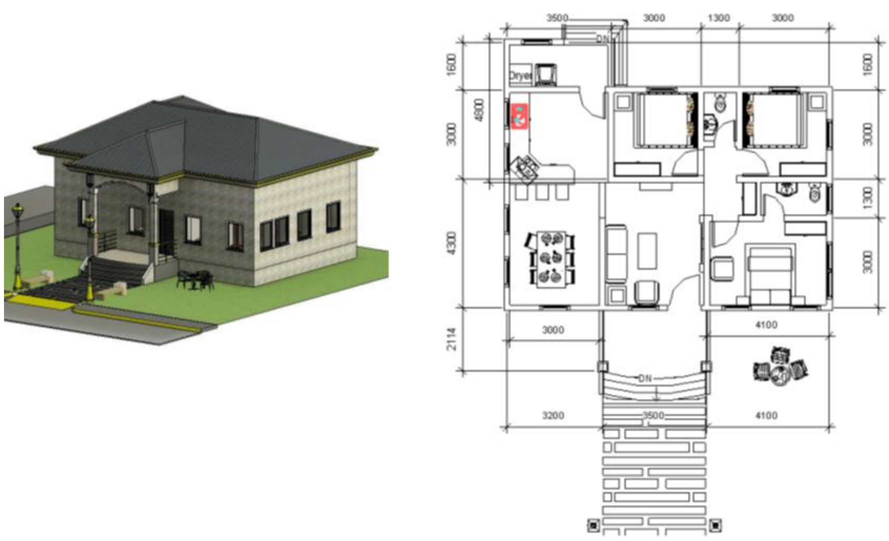
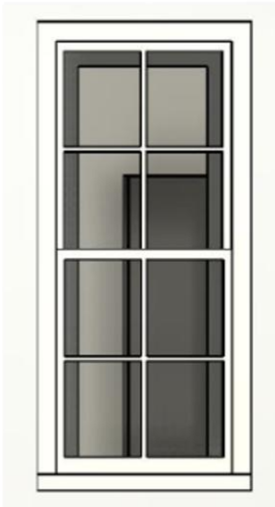
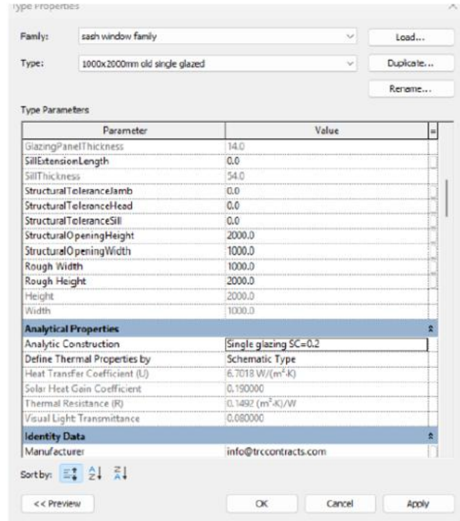


Fig. 1: Case study model 3D and Plan view



A Typical Shah Window

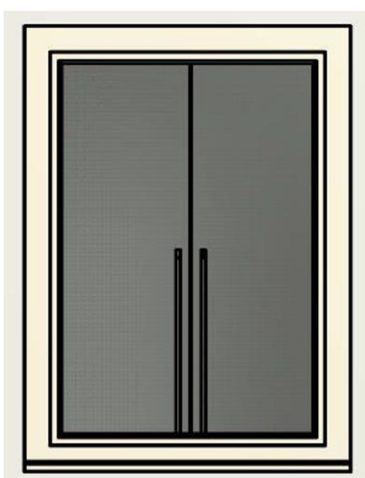


Case 1: Shah Window with Single Glazing (U Value 6.7)

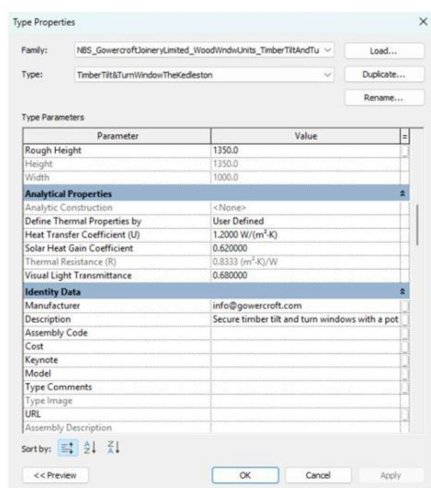
Fig 2: Example of a typical shah window and case 1 Modelling in the BIM

This study selected five window types for a comparative analysis, representing both traditional and modern alternatives, which include

1. Case 1: Original single-glazed sash and case window (U-value ≈ 6.7 W/m²K). Shown in Figure 2.
2. Case 2: New double-glazed sash window (U-value ≈ 1.4 W/m²K).
3. Case 3: New sash window with vacuum glazing (U-value ≈ 0.7 W/m²K).
4. Case 4: Refurbished sash window retrofitted with vacuum glazing (U-value ≈ 1.2 W/m²K).
5. Case 5: Modern tilt-and-turn uPVC window with double glazing (U-value ≈ 1.2 W/m²K). Shown in Fig. 3



Modern Tilt and Turn Window



Case 5: uPVC window with double glazing (U-value 1.2)

Fig 3: Example of modern title and turn window and Case 5 modelling in BIM

These window configurations were chosen to represent the different conservation options: a control of using the original window, full replacement with modern sash or uPVC, and advanced retrofitting using vacuum glazing. The building model was created in Autodesk Revit 2025 with windows integrated using heritage sash and case families sourced from NBS (a construction product database). Annual energy simulations were conducted using the Revit Insight 365 plugin, which applies region-specific weather data for Glasgow, Scotland. The tool calculates heating and cooling loads, thermal transmittance (rate of heat flow through materials), and operational energy demand across a 12-month cycle. Each scenario used consistent building fabric specifications (walls, roof, floors) to isolate the effect of window type. To ensure comparability, window positions and dimensions remained constant across all simulations. Simulation outputs included monthly and annual figures for heating demand, cooling demand, and overall energy consumption. These were analysed using descriptive statistics and comparative analysis to assess relative performance. The results were interpreted in relation to: (1) Thermal efficiency (heating/cooling reductions); (2) Alignment with regulatory standards of 1.4 W/m²K (HM Government, 2023); and (3) Suitability for conservation practice (heritage value vs sustainability).

This study is only considered one building type, and does not include factors such as occupant behaviour, air infiltration, and maintenance quality due to the limitations of the simulation environment. Despite these limitations, the approach provides robust comparative insights into the relative performance of sash window retrofits.

3. Results

The simulations produced annual heating and cooling demands for each window configuration (Figure 4). The results reveal clear distinctions between window types, particularly regarding heating and cooling demand, and help assess the trade-offs between energy efficiency, heritage preservation, and sustainability. Heating and cooling loads are critical performance indicators in historic buildings.

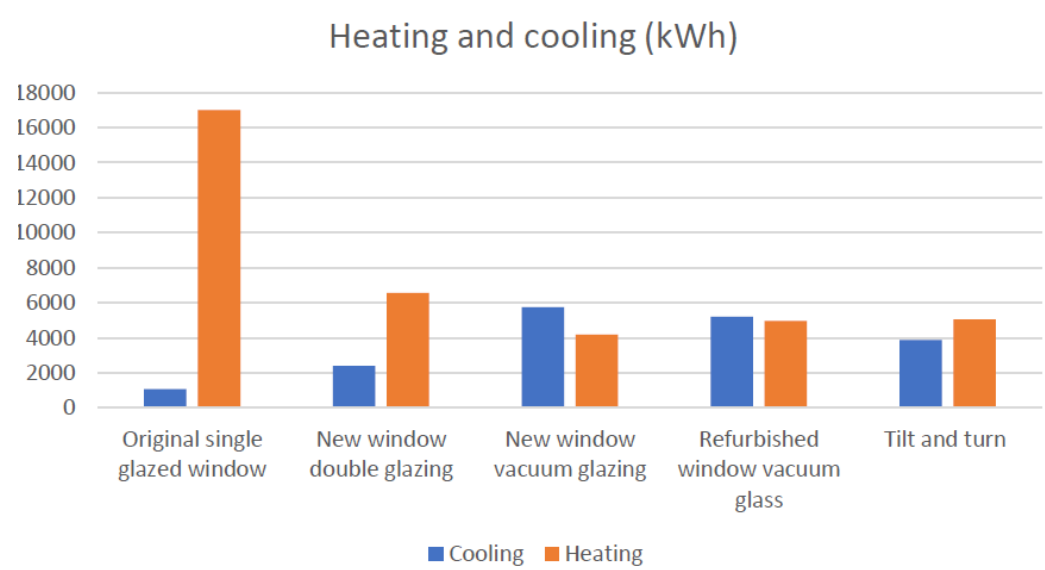


Fig 4: Heating and Cooling demand for all simulated cases

The results confirm that glazing type has a large impact on energy performance. The baseline single-glazed sash unsurprisingly performed poorly, while all retrofit and replacement options demonstrated substantial reductions in heating demand. However, improved insulation was also associated with increased cooling requirements, revealing an important trade-off for conservation practice. The traditional single-glazed sash window recorded the highest annual heating demand at 17,011 kWh and the lowest cooling demand at 1,069 kWh. The results align with the literature, where single-glazed windows have U-values typically around 4.8–6.8 W/m²K and are a significant source of heat loss in older buildings (Baker et al., 2010). A summary of simulation results is shown in Table 1.

Table 1. Summary of window performance (simulated).

Window type	U-value (W/m²K)	Type	Consumption (kWh)												
			Jan	Feb	Mar	Apr	May	Jun	Jul	Aug	Sep	Oct	Nov	Dec	**Total**
Original S&C window	6.7	Heating	2685	2111	1669	1540	1163	609	500	430	709	1230	1911	2448	**17005**
		Cooling	7	9	38	51	87	171	149	303	155	62	29	12	**1070**
New double glazed S&C	1.4	Heating	1255	993	703	470	245	99	56	81	159	455	785	1241	**6542**
		Cooling	8	10	63	111	208	436	493	616	317	95	34	13	**2405**
Refurb vacuum glazing	1.2	Heating	1106	797	484	254	93	27	12	31	78	320	644	1125	**4971**
		Cooling	9	22	184	366	613	937	1032	1113	644	203	47	14	**5183**
New S&C vacuum glazing	0.7	Heating	958	679	395	195	66	18	7	21	57	257	539	985	**4178**
		Cooling	9	30	220	429	700	1025	1124	1191	710	237	54	14	**5747**
Modern Tilt & turn with double glaizng	1.2	Heating	1077	804	508	289	119	40	21	39	89	327	635	1084	**5032**
		Cooling	9	13	118	234	419	709	790	890	497	151	41	14	**3885**

As shown in Table 1, the single-glazed typical sash and case window (Case 1) demonstrated the highest heating demand, exceeding 17,000 kWh annually. This reflects the well-documented inefficiencies of single glazing (Baker et al., 2010). Although cooling demand was minimal due to air leakage and poor airtightness, the configuration falls far short of regulatory standards (U = 6.7 W/m²K vs. the required 1.4 W/m²K). These findings reinforce the perception of original sash windows as energy liabilities and further support arguments for their replacement. In Case 2, the single glazing was replaced with double glazing in a sash window configuration, which reduced heating demand by approximately 60%, aligning performance with contemporary standards. However, cooling demand increased to approximately 2,400 kWh. This reflects reduced air infiltration and increased solar gain retention, which can lead to overheating during summer months. While thermal performance is markedly improved, this option requires full replacement of the historic features, weakening conservation principles, and increasing embodied carbon. Case 3 considered a new sash window with vacuum glazing, which significantly improved thermal efficiency, cutting heating demand by about 75% compared to the baseline Case 1. The very low U-value of 0.7 W/m²K enabled the modelled house to perform beyond current regulatory benchmarks. However, cooling demand rose sharply to about 5,700 kWh, which is the highest among all window configuration cases. This outcome illustrates a paradox of super-insulated heritage retrofits: while they reduce winter heat loss, they can create overheating risks without complementary ventilation strategies. This option also alters the building's historic image and increases its embodied carbon. Case 4 used a refurbished sash window retrofitted with vacuum glazing, demonstrating the performance benefits of entirely new vacuum-glazed sashes but with a lower cooling penalty. Heating demand was reduced to nearly 5,000 kWh, which is a significant reduction of 70%, while cooling demand stabilised at about 5,100 kWh compared to the baseline. Case 4 retained the original timber frames, preserving heritage authenticity and minimising the embodied carbon footprint. Case 5 used a modern uPVC tilt-and-turn window, which showed heating demand similar to Case 4 (~5,000 kWh) and moderate cooling demand (~3,900 kWh). However, it offered no heritage value and introduced additional embodied carbon due to PVC production. While efficient, it does not support cultural or sustainability goals, reinforcing arguments against widespread uPVC replacement in conservation areas.

4. Discussion

The study results showed that increasing insulation consistently reduces heating load but raises cooling demand, which aligns with the border retrofit literature (Fitton et al., 2017). However, sash windows provide several solutions to cooling demand. The ability to open both top and bottom sashes in summer creates a natural convection current of air.

Hot air rises out through the top sash and fresh cool air enters through the lower sash, cooling the space and improving air quality. Another solution to cooling demand is trickle vents, which can be installed on the window. These allow a constant movement of air that cools the area while still upholding the security a sash window provides (Biler et al., 2018). The refurbished sash with vacuum glazing proved to be the optimal compromise, delivering near-modern efficiency while retaining historic authenticity. This supports the position of conservation bodies such as Historic Environment Scotland (2018), who advocate for retention and upgrade rather than replacement. The study also showed the innovative potential of using vacuum glazing, which has proven to be transformative in terms of thermal performance, along with a slim profile and visual compatibility, making it uniquely suited to heritage applications, unlike bulky triple glazing. Its adoption, however, remains limited due to cost and availability. This highlights a need for policy and market intervention to make this product more affordable and attainable for the present market. Current building regulations often push toward replacement to achieve compliance in terms of thermal performance but ignore heritage value retention and broader environmental impacts, such as embodied carbon emissions. Findings from this study provide evidence that retrofitted sash windows can meet performance targets, suggesting scope for policy flexibility.

The study is based on simulation, which, while robust, cannot replicate real-world occupant behaviour, air infiltration, or maintenance quality. Additionally, only one building typology was analysed. Future research should expand to diverse building types, incorporate lifecycle cost assessments, and test acoustic and comfort impacts. Real-world demonstration projects would strengthen the case for large-scale adoption of vacuum glazing in heritage retrofits.

5. Conclusions

This study set out to evaluate the role of sash and case windows in balancing Scotland's heritage preservation priorities with modern sustainability requirements. Through a simulation-based approach, five glazing configurations were tested to compare their impact on heating and cooling demand. The results confirm the critical role that retrofitting plays in reconciling cultural authenticity with carbon reduction targets. The findings show that traditional single-glazed sash windows are highly inefficient, with heating demand exceeding 17,000 kWh annually. In contrast, interventions such as double glazing and vacuum glazing can reduce heating demand by up to 70%, achieving U-values compliant with the UK standards (HM Government, 2023). However, the study also highlights the trade-off between insulation and ventilation, with increased cooling demand in high-performance configurations. Among the options tested, the refurbishment of existing sash windows with vacuum glazing emerged as the most compelling solution. This approach preserved the historic fabric of the building and delivered near-modern levels of efficiency, reducing heating demand by over 70% while avoiding the heritage and embodied carbon losses associated with replacement. The findings suggest that heritage-sensitive retrofits can compete with modern uPVC alternatives while maintaining Scotland's cultural identity.

Despite the clear potential of vacuum glazing retrofits, several barriers currently limit widespread adoption. Cost remains the most significant, with vacuum glazing often priced three to four times higher than conventional double glazing, making it inaccessible for many homeowners without financial support. A persistent skills gap also exists, as relatively few craftspeople are trained to integrate advanced glazing into traditional sash and case frames without damaging historic fabric. Finally, regulatory hurdles pose challenges such as listed building consent and conservation planning processes that frequently favour like-for-like replacement rather than innovative retrofitting solutions, creating uncertainty for both practitioners and homeowners. Unless these barriers are addressed through targeted policy interventions, the scalability of heritage-sensitive retrofits will remain constrained. In addition, there is a need for practical incentives, training programs, and awareness campaigns, which could accelerate the adoption of advanced retrofits, such as in the case of sash windows in Scotland.

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