Strategies for Enhancing Energy Efficiency-cantered Environmental Sustainability through External Wall Structures of Historic Buildings. Case Studies from Edinburgh

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Abstract

Delving into all this in the urban context presents a multitude of challenges, the most prominent of them in the form of aged buildings of antiquity whose energy usage is a core argument of contention. As global carbon emissions continue to rise, the construction sector's critical role in driving the Sustainable Development Goals (SDGs) has become increasingly apparent. In this way the renovation and maintenance of a historic building, an intrinsic part of cultural heritage, should combine preservation of historical values with the durability of the new function and environmental aspect. This study aims to enhance the energy efficiency of historical structures by their external wall use and examination of environmental sustainability methods without compromising the historical integrity. Through piloting case study building types found in Edinburgh—Southbridge Resource and Education Centre, The Jenners Building and Holyrood Park Lodge—this research examines the impacts of material, interlocking and arrangement of walls on the thermal performance and longevity of the buildings. A comprehensive framework is created for the evaluation of the environmental efficiency of different wall forms using entropy-weighted and linear-weighted methods. The study emphasizes the importance of selecting appropriate materials and insulation techniques to reduce carbon footprints, improve energy efficiency and preserve the historical and cultural values of such buildings. The study points out that the careful selection of wall designs will not only contribute to their thermal optimization but will also facilitate in meeting the sustainability targets within sustainable long-term heritage management. To address these challenges, the study recommends geographically sustainable eco-remediation practices that help experts strike a balance between heritage conservation and environmental sustainability. The analysis combines new knowledge of insulation with culturally sensitive techniques and provides helpful guidance on enhancing sustain.

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Introduction

The concept of "sustainable development," introduced by Pezzey (1992), has attracted considerable attention in both academic and practical domains over recent decades.[1] In the 21st century, humanity has increasingly acknowledged that its survival is intricately tied to managing its relationship with nature, thereby underscoring the importance of environmental sustainability (Moldan et al., 2012).[2] Urban environments today face critical challenges, including excessive carbon emissions and high energy consumption, which exert significant pressure on environmental sustainability (Woon et al., 2023; Omer, 2009).[3] The building sector, as a major contributor to global greenhouse gas emissions, accounts for 32% of worldwide carbon emissions, with residential and non-residential buildings responsible for 50% and 32% of energy consumption, respectively.[4] As the global demand for sustainable development rises, the building industry plays a pivotal role in decarbonizing energy systems and advancing the objectives of the Paris Agreement and Sustainable Development Goals (SDGs).[5] The scientific community has made substantial progress in research aimed at reducing carbon emissions and improving energy efficiency.[6]For example, technological innovations have highlighted the feasibility of zero-carbon buildings as a transformative solution for advancing the sustainability of the construction industry. This is illustrated in Figure 1.[7] Additionally, the integration of advanced energy management systems and renewable energy technologies within the construction sector offers further pathways for achieving long-term environmental goals.[8]

1 John Pezzey, Sustainable Development Concepts: An Economic Analysis, World Bank Environment Paper, no. 2 (Washington, DC: The World Bank, 1992), http://documents.worldbank.org/curated/en/237241468766168949/Sustainable-development-concepts-an-economic-analysis.

2 Bedřich Moldan, Svatava Janoušková, and Tomáš Hák, "How to Understand and Measure Environmental Sustainability: Indicators and Targets," Ecological Indicators 17 (2012): 4-13, https://www.researchgate.net/publication/251678880_How_to_Understand_and_Measure_Environmental_Sustainability_Indicators_and_Targets.

3 Kok Sin Woon et al., "Recent Advances in Urban Green Energy Development Towards Carbon Emissions Neutrality," Energy 267 (2023): 126502, https://scholar.google.com.sg/citations?user=3EWYy_EAAAAJ&hl=en[1](https://scholar.google.com.sg/citations?user=3EWYy_EAAAAJ&hl=en); Abdeen Mustafa Omer, "Energy Consumption, Environment and Sustainable Development," in Proceedings of the 3rd International Conference on Sustainable Energy and Environmental Protection (SEEP 2009), Dublin, 12-15 August 2009, p. 1011

4 IPCC. Climate Change 2022: Mitigation of Climate Change. Contribution of Working Group III to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press, 2022. https://www.ipcc.ch/report/ar6/wg3/chapter/chapter-9/.

5 UNFCCC. 2023 Global Status Report for Buildings and Construction. United Nations Framework Convention on Climate Change, 2023. https://unfccc.int/ttclear/misc_/StaticFiles/gnwoerk_static/tn_meetings/00cf22a4049c4ece9f414e190def4202/8dff87ea3e1e4e7ba7d349a83ed04cbd.pdf.

6 IPCC, Climate Change 2022: Mitigation of Climate Change, 2022.

7 Ibid.

8 Ibid.

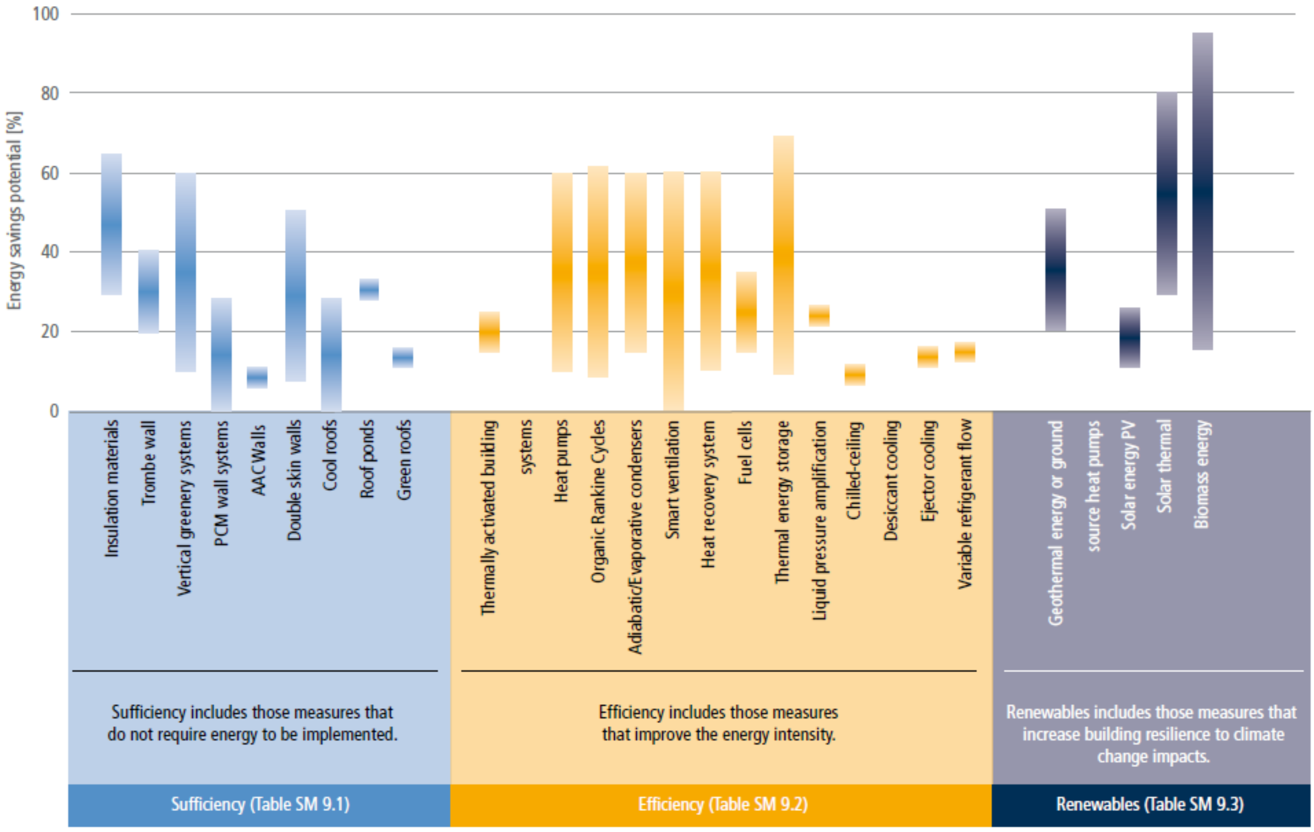

Figure 1, ‘Energy savings potential of technology strategies for climate change mitigation in buildings,’ in Trisos, C.H., I.O. Adelekan, E. Totin, A. Ayanlade, J. Efitre, A. Gemeda, K. Kalaba, C. Lennard, C. Masao, Y. Mgaya, G. Ngaruiya, D. Olago, N.P. Simpson, and S. Zakieldeen, 2022: Africa. In: Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, pp. 1285–1455, doi:10.1017/9781009325844.011. https://www.ipcc.ch/report/ar6/wg3/figures/chapter-9/figure-9-11

Existing buildings present substantial potential for improving energy efficiency and reducing carbon emissions, thereby advancing the sustainability of the construction industry.[9] For instance, the United Kingdom, renowned for its cultural heritage, has approximately 400,000 historic buildings listed for conservation.[10] These structures not only embody significant cultural and historical value but also contribute approximately 5% of the United Kingdom’s total carbon emissions. In Scotland, historic buildings hold even greater significance, comprising approximately 37.8% of the UK’s building stock and contributing up to 57.4% of overall carbon emissions through energy use.[11] These figures underscore the critical role of historic buildings in shaping sustainable development strategies, particularly as climate change imposes increasing demands for environmentally responsible construction practices.

9 Panakaduwa, Chamara, Paul Coates, and Mustapha Munir. "Identifying Sustainable Retrofit Challenges of Historical Buildings: A Systematic Review." Energy and Buildings 313 (2024): 114226. https://doi.org/10.1016/j.enbuild.2024.114226.
10 bid.
11 Scottish Environment Protection Agency. “Historic Environment.” In Our Environment. Accessed October 25, 2024. https://www.environment.gov.scot/our-environment/people-and-the-environment/historic-environment/.

Conserving and renovating historic buildings has emerged as a critical architectural focus in light of the pressing challenges posed by climate change.[12] Architectural professionals face the dual challenge of preserving the cultural and historical value of these buildings while ensuring their adaptation to modern societal needs and compliance with stringent environmental regulations. [13]The Royal Institute of British Architects (RIBA) 2021 recommendations advocate for steering the construction industry toward sustainability by prioritizing renovation over demolition, a process that wastes resources and exacerbates carbon emissions. This shift reflects a growing recognition of the environmental benefits of retrofitting existing structures, which often involve significantly lower carbon footprints compared to new construction. [14]

Furthermore, stringent regulations have been implemented to balance modern requirements with the preservation of historic building characteristics.[15] These regulations encompass a range of considerations, including the preservation of facades, moderate internal structural modifications, and material consistency to retain the buildings' aesthetic and historical authenticity.[16] Advanced retrofitting techniques, such as energy-efficient glazing, enhanced insulation, and renewable energy systems, are increasingly being employed to modernize these structures while maintaining their original integrity.[17] Thus, renovating historic buildings represents not only a physical renewal but also an opportunity to reassess cultural heritage and environmental integration. By addressing these challenges through innovative technologies and collaborative efforts, the conservation of historic buildings can serve as a model for achieving sustainability while honoring architectural and cultural history.[18]

The façade, as the most visually prominent feature of a historic building, serves as the primary interface for heat exchange and plays a crucial role in influencing the building's overall energy consumption and carbon emissions.[19] Its material composition and structural design significantly affect the environmental performance of the entire building.[20] Focusing on the façade as the primary subject of study facilitates a more comprehensive evaluation and optimization of a building's environmental sustainability. This approach allows researchers and practitioners to address key challenges in reducing energy consumption and carbon emissions without compromising the historical value of the structure.

12 Panakaduwa, Coates, and Munir, "Identifying Sustainable Retrofit Challenges," 114226.

13 Merlino, Kathryn Rogers. "[Re]Evaluating Significance: The Environmental and Cultural Value in Older and Historic Buildings." The Public Historian 36, no. 3 (2014): 70-85. https://www.jstor.org/stable/pdf/10.1525/tph.2014.36.3.70.pdf.

14 Royal Institute of British Architects (RIBA). RIBA 2030 Climate Challenge Version 2 (2021). https://www.architecture.com/-/media/files/Climate-action/RIBA-2030-Climate-Challenge.pdf.

15 City of Edinburgh Council. Listed Buildings and Conservation Areas Guidance. 2022. https://consultationhub.edinburgh.gov.uk/sfc/conservation-adaptation2023/supporting_documents/Listed_Buildings_Guidance_14_October_2022.pdf.

16 Ibid.

17 Historic England, "Energy Efficiency and Retrofit in Historic Buildings," last modified July 31, 2024, https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/.

18 IPCC, Climate Change 2022: Mitigation of Climate Change, 2022.

19 Gianluca Mortarotti, Michele Morganti, and Carlo Cecere. "Thermal Analysis and Energy-Efficient Solutions to Preserve Listed Building Façades: The INA-Casa Building Heritage." Buildings 7, no. 3 (2017): 56. https://doi.org/10.3390/buildings7030056.

20 Milan Porhinčák and Adriana Eštoková, "Comparative Analysis of Environmental Performance of Building Materials Towards Sustainable Construction," Chemical Engineering Transactions 35 (2013): 1291-1296, https://www.aidic.it/cet/13/35/215.pdf.

Firstly, the choice of materials in the renovation of historic buildings is a critical factor in assessing environmental sustainability. The production, transportation, and installation of materials contribute substantially to greenhouse gas emissions and grey energy consump-tion.[21] For instance, materials such as concrete and steel, commonly utilized in modern construction, generate considerable carbon emissions over their entire lifecycle, necessi-tating careful consideration and calculation of their environmental impacts by architects.[22] Thus, the selection and application of façade materials influence not only the thermal per-formance of a building but also its overall carbon footprint.[23] Utilizing sustainable materials with low embodied energy, such as reclaimed wood or advanced composites, can significantly reduce emissions while maintaining structural integrity.[24] Secondly, external wall structures typically comprise a protective outer layer, an insulating layer, and an internal support framework, which collectively determine the building's thermal performance and energy efficiency.[25] Effective design and material selection for these layers are critical to minimizing heat loss and maximizing energy conservation.[26] The study of façades has become a focal point for practitioners, emphasizing the selection and combination of low-carbon materials to minimize lifecycle carbon emissions while meeting diverse functional requirements. Incor-porating innovative technologies, such as dynamic insulation systems and solar-integrated façades, further enhances their environmental performance.

This approach preserves the historical integrity of the building while simultaneously improving its environmental sustainability. By addressing the dual challenges of conservation and energy efficiency, the renovation of historic building façades represents a pivotal strategy in advancing sustainable architecture. These efforts underscore the importance of integrating environmental objectives with cultural heritage preservation to achieve long-term sustainability goals.

This research aims to explore the influence of façade design, structural configurations, and material selection in historic buildings of varying uses on sustainable development. The study begins by outlining the background, motivation, and objectives, emphasizing the critical role of façade materials and structures in historic buildings, particularly their contribution to sustainable development. The analysis highlights the potential of façade refurbishment as a key intervention point for improving energy efficiency and reducing carbon emissions while maintaining the cultural and historical integrity of these structures. Subsequently, a systematic literature review establishes the theoretical foundation for understanding the sustainability impacts of materials and wall structures during historic building renovations. This review identifies existing research gaps, explores the challenges associated with current applications, and provides the necessary basis for further investigation. Through this process, the study contextualizes the complexities of balancing heritage preservation with modern sustainability requirements.

21 Wang, Guohao, et al. "A Comprehensive Review of Building Lifecycle Carbon Emissions and Reduction Approaches." City and Built Environment 2, Article number: 12 (2024). https://link.springer.com/article/10.1007/s44213-024-00036-1.
22 Ibid.
23 Toktam Bashirzadeh Tabrizi et al., "The Impact of Different Insulation Options on the Life Cycle Energy Demands of a Hypothetical Residential Building," Procedia Engineering (2017), https://www.sbe16sydney.be.unsw.edu.au/Proceedings/33326.pdf.
24 Joseph Abed, Scott Rayburg, John Rodwell, and Melissa Neave, "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures," Sustainability 14, no. 9 (2022): 5570, https://www.mdpi.com/2071-1050/14/9/5570.
25 Kiviste, "Effect of Solar Radiation on Thermal Performance of External Wall Structures Based on Long-Term Measured Data," Tampere University (2020), https://trepo.tuni.fi/bitstream/handle/10024/129702/Kiviste_Effect_of_solar_radiation_on_thermal_performance_of_external_wall_structures_based_on_long_term_measured_data.pdf.
26 Ibid.

The methodology involves selecting three historic building refurbishment cases in Edinburgh, encompassing diverse uses such as activity centers, commercial spaces, and cultural institutions. Data analysis methods will be employed to evaluate the impact of various façade configurations and material applications on energy consumption. Particular attention will be paid to the thermal performance, lifecycle carbon footprint, and overall environmental impact of different materials and structural designs. A key component of this research is the collection and analysis of sustainability data for different façade constructions, aiming to identify optimal configurations suitable for refurbishment and aligning with long-term sustainability goals. Finally, the research will synthesize findings from the data and case studies to propose façade design strategies tailored to the refurbishment of historic buildings in Edinburgh. These strategies aim to guide architects and policymakers in adopting sustainable façade refurbishment solutions. By facilitating the low-carbon transformation of historic buildings, these strategies not only contribute to the preservation of cultural heritage but also play a critical role in advancing broader carbon neutrality objectives and sustainable urban development. This work provides a framework for integrating environmental sustainability with heritage conservation, addressing the dual challenge of preserving the past while building a sustainable future.

Review of Literature

The central focus of this study lies in the integration and interplay of "Environmental Sustainability," "Historic Buildings," and "Construction Materials" (Figure 2). Environmental sustainability entails the responsible utilization of resources and the preservation of ecological balance while meeting present and future economic, social, and environmental needs (RICS Research Trust, 2020).[27] Historic buildings are structures of significant historical, cultural, or architectural value, embodying the cultural and historical narratives of their communities and serving as tangible connections to the past.[28] These buildings are distinguished by construction techniques and materials specific to their era, which are crucial for preserving their integrity during restoration or alteration processes (Zeayter and Mansour, 2018).[29]

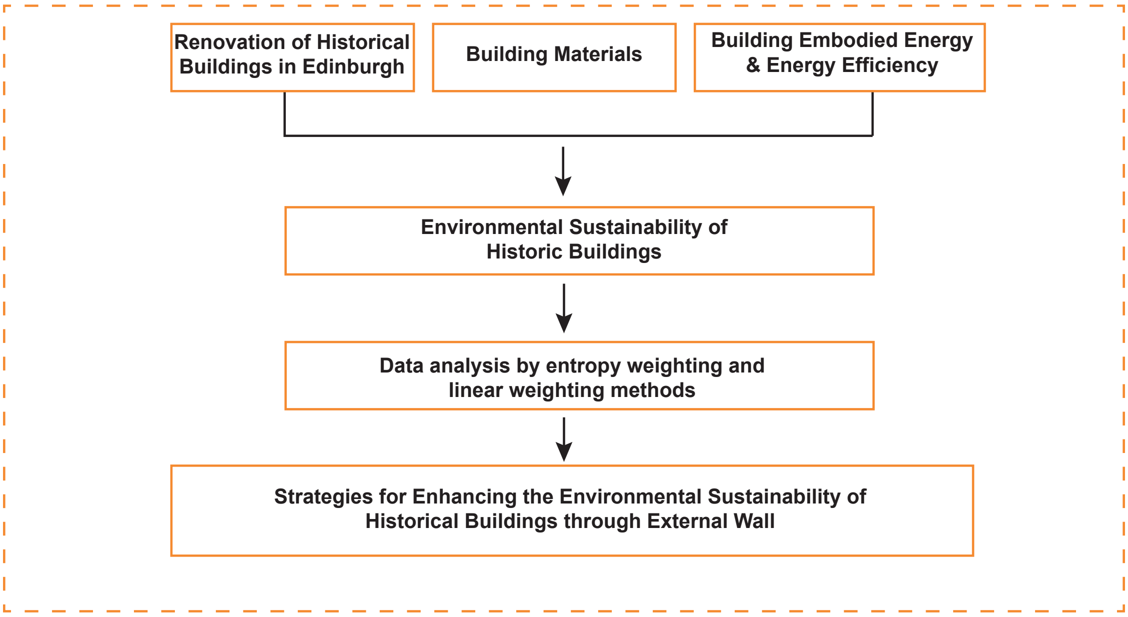

Figure 2, Research workflow,used to explain the description of the research process and framework, drawn by the authors

27 RICS Research Trust. "The UN Sustainable Development Goals – a Common Language for Land, Construction and Real Estate." https://www.rics.org/content/dam/ricsglobal/documents/to-be-sorted/implementing-un-sustainable-development-goals-rics.pdf.

28 "The UNESCO World Heritage Site." https://ewh.org.uk/the-unesco-world-heritage-site/.

29 Hoda Zeayter and Ashraf Mansour Habib Mansour. "Heritage Conservation Ideologies Analysis – Historic Urban Landscape Approach for a Mediterranean Historic City Case Study." HBRC Journal 14, no. 3 (2018): 345-356. https://doi.org/10.1016/j.hbrcj.2017.06.001.

Historic building alteration involves adapting buildings of historical, cultural, and social significance, ensuring compatibility with their heritage values while modernizing them for contemporary use.[30] Building materials constitute the foundation of an e, and their properties, sources, and environmental impacts are integral to the overall sustainability of a building.[31] This study posits that strategies to improve the environmental sustainability of historic buildings must incorporate the performance of building materials concerning energy efficiency, resource utilization, and environmental impact to achieve a balanced integration of these elements. While existing research highlights the critical role of material selection in historic building conversion, practical guidelines addressing diverse building types and geographical contexts remain insufficient. This review will critically examine existing literature, identify the key components of sustainable material selection, and offer recommendations for future research and practical applications. By bridging the gap between theoretical understanding and practical implementation, this study aims to provide a framework for enhancing the sustainability of historic buildings while preserving their cultural and historical significance.

This research aims to demonstrate that the environmental sustainability of historic buildings is shaped by several interconnected factors, such as energy efficiency, material selection, cultural significance, and regulatory frameworks.[32] Energy efficiency plays a pivotal role in achieving sustainability within historic buildings.[33] Research indicates that enhancing energy efficiency can reduce the economic costs associated with building operations while simul-taneously improving occupant satisfaction (Karimi et al., 2022).[34] Nevertheless, current sustainability assessment systems frequently neglect regional climatic variations and the intrinsic cultural values of buildings.[35] This oversight often undervalues the long-term eco-nomic and societal contributions of historic buildings (Pracchi, 2014; IHBC, 2020; Zeayter and Mansour, 2018).[36] Policy support and market-based incentives are crucial for motivating designers and architects to consider the full lifecycle impacts of materials when making their selections.[37] Such measures ensure that material choices not only minimize environmental footprints but also deliver social and economic benefits.[38] However, low-carbon materials, despite their theoretical environmental advantages, frequently face challenges such as high costs, limited availability, and low market acceptance.[39] This underscores the importance of future research and practice adopting a collaborative approach to balance environmental protection with commercial realities in promoting sustainable buildings.[40]

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30 Mehr, Shabnam Yazdani. "Analysis of 19th and 20th Century Conservation Key Theories in Relation to Contemporary Adaptive Reuse of Heritage Buildings." Heritage 2, no. 1 (2019): 920-937. https://doi.org/10.3390/heritage2010061.

31 Wang et al., "Building Lifecycle Carbon Emissions."

32 Taher Tolou Del, Mohammad Sadegh, Bahram Saleh Sedghpour, and Sina Kamali Tabrizi. "The Semantic Conservation of Architectural Heritage: The Missing Values." Heritage Science 8, Article number: 70 (2020). https://heritagesciencejournal.springeropen.com/articles/10.1186/s40494-020-00416-w.

33 Historic England, "Energy Efficiency and Retrofit."

34 Karimi, F., Valibeig, N., Memarian, G., and Kamari, A. "Sustainability Rating Systems for Historic Buildings: A Systematic Review." Sustainability 14 (2022): 12448. https://doi.org/10.3390/su141912448.

35 Valeria Pracchi, "Historic Buildings and Energy Efficiency," The Historic Environment: Policy & Practice 5, no. 2 (2014): 210-225, https://doi.org/10.1179/1756750514Z.00000000052.

36 Pracchi, "Historic Buildings and Energy Efficiency."; Institute of Historic Building Conservation (IHBC), "Sustainability and Conservation of the Historic Built Environment," April 2020, https://ihbc.org.uk/toolbox/position_statement/sustainablilityconservation.html.; Zeayter and Mansour, "Heritage Conservation Ideologies Analysis," 345-356.

37 Yuan Li et al., "Research Frameworks, Methodologies, and Assessment Methods Concerning the Adaptive Reuse of Architectural Heritage: A Review," Built Heritage 5, Article number: 6 (2021), https://built-heritage.springeropen.com/articles/10.1186/s43238-021-00025-x.

38 Ibid.

39 B.V. Venkatarama Reddy, "Sustainable Materials for Low Carbon Buildings," International Journal of Low-Carbon Technologies 4, no. 3 (2009): 175-181, https://academic.oup.com/ijlct/article/4/3/175/710965.

40 Li et al., "Adaptive Reuse of Architectural Heritage."

Cultural and social factors are equally crucial.[41] Preserving the cultural value of historic buildings during energy efficiency retrofits is essential to maintaining their heritage integrity (Pracchi, 2014).[42] Public and community involvement plays a pivotal role in sustainable preservation, enhancing the daily functionality of historic buildings and fostering a sense of engagement among occupants (Zeayter and Mansour, 2018).[43] Community participation also helps ensure that the needs and preferences of local stakeholders are adequately consid-ered, promoting long-term stewardship of these heritage assets.[44] Achieving environmental sustainability in historic buildings is a complex task requiring multidimensional compromises and balance.[45] Energy efficiency, cultural value preservation, material selection, and public participation must be holistically integrated into policy-making and practice to achieve genuine sustainable development.[46] By addressing these factors collectively, stakeholders can develop comprehensive strategies that align environmental goals with cultural and economic priorities, paving the way for the sustainable preservation of historic buildings.[47]

Existing research highlights the extensive use of materials such as stone, brick, timber, soil, lime, and metal in historic buildings, which not only define their physical structure but also contribute significantly to their cultural and historical significance.[48] For instance, stone and soil, often used as mortar, are predominant materials in historic English buildings, with soil mortar demonstrating exceptional efficacy, particularly in medieval construction.[49] Studies suggest that material choices must align with local climatic and cultural contexts to enhance a building's historical value and social identity.[50] Additionally, these choices significantly influence thermal performance and energy efficiency, both critical for sustainability in historic buildings.[51]

Materials like adobe (mud bricks) and timber excel in maintaining structural stability and durability. However, they demand appropriate restoration and maintenance strategies to address challenges such as moisture and pest intrusion (Vissilia & Villi, 2010).[52] Similarly, lime and clay, as traditional building materials, remain reliable options for historic buildings due to their adaptability to diverse environmental conditions and their reusability.[53] Moreover, traditional materials like wood, masonry, and concrete are integral to the lifecycle of historic buildings, influencing material extraction, transportation, construction, maintenance, and eventual demolition or waste management.[54] Their use minimizes resource reinvestment and energy consumption, consequently lowering carbon emissions.[55] However, the selection of materials often encounters supply chain challenges, particularly

41 Pracchi, "Historic Buildings and Energy Efficiency."
42 Ibid.
43 Zeayter and Mansour, "Heritage Conservation Ideologies Analysis," 345-356.
44 Ibid.
45 Magrini, A., and Franco, A. "The Energy Performance Improvement of Historic Buildings and Their Environmental Sustainability Assessment." Journal of Cultural Heritage 21 (2016): 1-8. https://doi.org/10.1016/j.culher.2016.03.012.
46 Ibid.
47 Ibid.
48 Historic England, "Properties of Traditional Building Construction," https://historicengland.org.uk/advice/technical-advice/retrofit-and-energy-efficiency-in-historic-buildings/traditional-buildings-and-energy-efficiency/properties-of-traditional-building-construction/; Historic Environment Scotland. "Scotland's Traditional Building Materials: A Consideration of Current Provision, Challenges and Opportunities." https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=d528a605-e25a-4824-933d-a77700968f1f.
49 Ibid.
50 Shweta Choudhary, Satish Pipralia, and Nand Kumar, "Need for Integrated Approach for Energy Efficiency Assessments and Material Evaluation of Historic Buildings," Materials Today: Proceedings 42, no. 4 (2021): 1727-1731, https://doi.org/10.1016/j.matpr.2020.10.664.
51 Ibid.
52 Anna-Maria Vissilia and Maria Villi, "Adobe and Timber Ties as Main Construction Materials for an Historic Greek Dwelling," International Journal of Architectural Heritage 4, no. 4 (2010): 295-319, https://doi.org/10.1080/15583050902934973.
53 Historic Environment Scotland. "Scotland's Traditional Building Materials: A Consideration of Current Provision, Challenges and Opportunities." https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=d528a605-e25a-4824-933d-a77700968f1f.
54 Berg and Fuglseth, "Life Cycle Assessment and Historic Buildings," 152-167; Conejos, Sheila, Craig Langston, and Jim Smith. "Designing for Future Buildings: Adaptive Reuse as a Strategy for Carbon Neutral Cities." The International Journal of Climate Change: Impacts and Responses 3, no. 2 (2012): 33-52. https://doi.org/10.18848/1835-7156/CGP/v03i02/37139.
55 Ibid.

regarding sustainability and cost.[56] For instance, Scotland, despite its abundant lime and timber resources, relies heavily on imported construction materials, contributing to a significant carbon footprint.[57] Consequently, the limited availability of indigenous materials not only elevates construction costs but also impedes the progress of sustainable building projects.[58] As a result, indigenous materials are predominantly utilized in high-end projects, while most restoration works depend on imported alternatives.[59]

In summary, the appropriate selection and utilization of traditional materials preserve the cultural and aesthetic value of historic buildings while simultaneously fostering local economic development.[60] This necessitates an integrated materials management strategy that balances the retention of cultural identity with the principles of environmental sustainability. By addressing these challenges holistically, stakeholders can develop more sustainable approaches to historic building restoration that benefit both cultural heritage and environmental conservation.[61]

The selection and combination of materials play a pivotal role in influencing energy consumption during building construction, particularly in the renovation of historic buildings.[62] The application of internal wall insulation is especially effective in enhancing the thermal performance of multi-storey historic buildings.[63] For example, insulating solid brick walls can increase surface temperatures, narrow the temperature gap between indoor air and walls, enhance occupant comfort, and reduce the heat transfer coefficient by up to 40%.[64] For instance, in the Settequerce building, 8 cm thick wood fibre insulation boards adhered to the interior of stone walls significantly improve thermal performance, reducing heat loss during winter. When combined with existing materials such as 4 cm thick external plaster and 44 cm thick red porphyry brick masonry, these insulation boards form a composite wall structure that optimizes energy efficiency.[65]

The thermal performance of walls is closely linked to insulation thickness.[66] While increased thickness enhances thermal resistance, it can also intensify hot and humid conditions, resulting in elevated relative humidity, increased energy losses from higher heating demands, and heightened risks of frost damage and mould growth.[67] Consequently, careful monitoring of humidity and temperature conditions is essential to prevent such adverse effects.[68] Wall insulation systems exhibit varying performances based on humidity and thermal conditions, which directly influence overall energy efficiency.[69] For instance, vapour-proof systems like glass-foam offer strong performance with minimal risk, improving thermal comfort and reducing heating energy consumption.[70] In contrast, open systems, such as aerated concrete, may present increased risks in high-humidity

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56 Historic Environment Scotland. "Scotland's Traditional Building Materials: A Consideration of Current Provision, Challenges and Opportunities." https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=d528a605-e25a-4824-933d-a77700968f1f.
57 Ibid.
58 Ibid.
59 Ibid.
60 Ibid.
61 Ibid.
62 Daniel Herrera-Avellanosa et al., "Evaluating the Implementation of Energy Retrofits in Historic Buildings: A Demonstration of the Energy Conservation Potential and Lessons Learned for Upscaling," Heritage 7, no. 2 (2024): 997-1013, https://www.mdpi.com/2571-9408/7/2/48.
63 Tommy Odgaard, Søren Peter Bjarløv, and Carsten Rode, "Interior Insulation – Experimental Investigation of Hygrothermal Conditions and Damage Evaluation of Solid Masonry Façades in a Listed Building," Building and Environment 129 (2018): 1-14, https://doi.org/10.1016/j.buildenv.2017.11.015.
64 Ibid.
65 Simone Panico et al., "Long-term Monitoring Data of Hygrothermal Conditions of a Retrofitted Historic Building in Settequerce, South Tyrol (Italy)," Journal of Building Engineering 50 (2024): 104-118, https://doi.org/10.1016/j.jobe.2024.104109.
66 Odgaard, Bjarløv, and Rode, "Interior Insulation," 1-14.
67 Simone Panico et al., "Long-term Monitoring Data of Hygrothermal Conditions of a Retrofitted Historic Building in Settequerce, South Tyrol (Italy)," Building and Environment 129 (2018): 1-14, https://doi.org/10.1016/j.buildenv.2017.11.015 ; Odgaard, Bjarløv, and Rode, "Interior Insulation," 1-14.
68 Ibid.
69 Ibid.
70 Ibid.

environments.[71] Additionally, the coatings applied to exterior wall materials significantly impact energy consumption.[72] For instance, waterproof coatings enhance thermal comfort and promote energy savings by minimizing heat transfer.[73] Such coatings improve the durability and energy efficiency of wall structures, particularly in regions prone to extreme weather conditions.[74] By integrating insulation materials and exterior coatings effectively, the renovation of historic buildings can simultaneously address energy efficiency, occupant comfort, and environmental sustainability.[75] Ultimately, selecting appropriate material combinations and implementing robust insulation and coating strategies are essential for achieving sustainable energy performance in historic buildings.[76] These efforts contribute not only to reducing carbon emissions but also to preserving the structural and cultural integrity of historic architecture.[77]

This chapter examines the interconnectedness of environmental sustainability, historic buildings, and building materials, highlighting the critical role of integrating material selection and performance in improving the environmental sustainability of historic properties (RICS Research Trust, 2020).[78] Designers and architects must leverage multidimensional data to devise adaptable material combinations for renovating historic buildings, addressing the dual challenges of modernization and cultural heritage preservation (Bullen & Love, 2011).[79] The renovation of historic properties presents unique challenges that require innovative approaches to balance environmental performance with the cultural and historical significance of these structures.[80] Moreover, the use of traditional materials, recognized for their durability and low-carbon characteristics, is vital in minimizing environmental footprints.[81] These materials play a significant role in achieving economic resource savings by reducing reliance on new construction, while also preserving the cultural identity embedded in their use.[82] For instance, materials such as stone, lime, and timber not only reflect regional heritage but also exhibit properties that align well with modern sustainability goals, such as reusability and adaptability to diverse environmental conditions.[83] By incorporating traditional materials into renovation practices, designers can create strategies that simultaneously preserve historic authenticity and achieve environmental sustainability.[84]

Sustainability in historic properties extends beyond technical considerations; it is deeply intertwined with socio-political and economic factors that shape material availability and selection practices (Bullen & Love, 2011).[85] Challenges such as fluctuating material costs, limited availability of indigenous resources, and dependence on imported materials can significantly influence the feasibility of sustainable renovation projects.[86] Furthermore, policymakers and communities play a cru-

71 Ibid.

72 Sebastian Malz, Walter Krenkel, and Oliver Steffens, "Infrared Reflective Wall Paint in Buildings: Energy Saving Potentials and Thermal Comfort," Energy and Buildings 224 (2020): 110212, ISSN 0378-7788, https://doi.org/10.1016/j.enbuild.2020.110212. (https://www.sciencedirect.com/science/article/pii/S0378778820309038).

73 Panagiota Pagoni, Eva Birgit Møller, Ruut Hannele Peuhkuri, and Nickolaj Feldt Jensen, "Evaluation of the Performance of Different Internal Insulation Systems in Real-Life Conditions - A Case Study," Building and Environment 267, Part C (2025): 112319, ISSN 0360-1323, https://doi.org/10.1016/j.buildenv.2024.112319. (https://www.sciencedirect.com/science/article/pii/S0360132324011612).

74 Ibid.

75 Odgaard, Bjarløv, and Rode, "Interior Insulation," 1-14 ;

76 Ibid.

77 Ibid.

78 RICS Research Trust, "The UN Sustainable Development Goals – a Common Language for Land, Construction and Real Estate."

79 Peter A. Bullen and Peter E.D. Love, "Adaptive Reuse of Heritage Buildings," Structural Survey 29, no. 5 (2011): 411-421, https://doi.org/10.1108/02630801111182439.

80 Ibid.

81 Jocelyn A. Rivera-Lutap, Orlean G. Dela Cruz, Jhun M. Jacinto, Leslie Mae D. Vael, and Manuel M. Muhi, "Alternative Building Materials for a Sustainable Built Environment: A Literature Review," in Proceedings of the 10th International Conference on Energy Engineering and Environmental Engineering (Springer, 2024), 235-246, https://link.springer.com/chapter/10.1007/978-3-031-48204-5_20.

82 Historic Environment Scotland, "Scotland's Traditional Building Materials."

83 Ibid.

84 Ibid.

85 Bullen and Love, "Adaptive Reuse of Heritage Buildings," 411-421.

86 Historic Environment Scotland, "Scotland's Traditional Building Materials."

cial role in these efforts.[87] Their involvement is essential to foster public participation in preserving cultural values and strengthening the connection between historic buildings and the communities they serve (Zeayter & Mansour, 2018).[88] Active community engagement not only ensures that local perspectives are represented but also promotes long-term stewardship of historic properties.[89] While existing studies offer a valuable theoretical foundation for understanding sustainability in the renovation of historic buildings, the evaluation of material interactions and the systemic impacts of these choices remain underexplored. Future research must focus on developing integrated frameworks that consider the interplay between material properties, energy performance, and cultural significance. Such frameworks would provide practitioners with practical guidelines for selecting materials that balance environmental goals with the preservation of historic identity. By addressing these gaps, stakeholders can ensure that the renovation of historic buildings contributes meaningfully to broader sustainability objectives while respecting their cultural and historical legacies.

Methods and Materials

The primary site of this study is Edinburgh, the capital of Scotland, located on the southern shore of the Firth of Forth along Scotland's eastern coastline, at latitude 55.953251°N and longitude 3.188267°W (Figure 3).[90] Edinburgh is divided into two distinct areas: the Old Town and the New Town. The Old Town, dominated by the iconic Edinburgh Castle, reflects a medieval urban layout, while the New Town is renowned for its Georgian architecture, characterized by neoclassical design and symmetrical planning.[91] Both the Old and New Towns were designated UNESCO World Heritage Sites in 1995 due to their cultural and historical significance.[92] Edinburgh experiences a temperate maritime climate, characterized by mild and humid conditions year-round, with cool summers averaging 20°C and winters ranging between 0°C and 7°C.[93] Precipitation is relatively uniform throughout the year, with no specific season experiencing significantly higher rainfall. The city's proximity to the sea results in consistent winds year-round, with stronger sea breezes particularly prevalent during winter months.[94]

Edinburgh, Scotland, UK
Geographic Information

Country	United Kingdom
Latitude	55.953251
Longitude	-3.188267
DMS Lat	55° 57' 11.7036'' N
DMS Long	3° 11' 17.7612'' W
UTM Easting	488,244.04
UTM Northing	6,200,892.57
Category	Cities
Country Code	GB
Zoom Level	10

Figure 3, Edinburgh geographic map and location information, Image from: "Edinburgh Geographic Map and Location Information," LatLong.net, https://www.latlong.net/place/edinburgh-scotland-uk-2533.html; "Edinburgh Maps and Directions," Film Edinburgh, https://www.filmedinburgh.org/Filming/Maps-Directions.

87 Li et al., "Adaptive Reuse of Architectural Heritage."
88 Zeayter and Mansour, "Heritage Conservation Ideologies Analysis," 345-356.
89 Ibid.
90 "Where is Edinburgh, Scotland, UK on Map Lat Long Coordinates," LatLong.net, https://www.latlong.net/place/edinburgh-scotland-uk-2533.html
91 Edinburgh World Heritage. "The UNESCO World Heritage Site." https://ewh.org.uk/the-unesco-world-heritage-site/.
92 Ibid.
93 Lynch, Michael. "Edinburgh - Maritime, Temperate, Rainy." Encyclopaedia Britannica. https://www.britannica.com/place/Edinburgh-Scotland/Climate.
94 Ibid.

The criteria for selecting case studies encompassed their historical and cultural significance, as well as their building type and functional use. These criteria ensure that the selected buildings represent a diverse range of architectural styles, construction methods, and usage scenarios. The selected buildings aim to facilitate a comprehensive evaluation of the retrofit strategy's applicability across varying contexts and functional uses. This approach allows for the identification of tailored solutions that address specific challenges while ensuring the preservation of cultural and historical value.

Case Study 1 - Multi-purpose academic and research space

South Bridge Resource and Education Centre, located at 6 Infirmary Street, EH1 1LS in Edinburgh's Old Town, is a Grade B listed historic building built in 1885 and originally used as a school.[95] (Figure 4) The building is a Gothic L-shaped structure with a triple peaked roof and central bell tower, and a facade of carved sandstone and contrasting stone dressings.[96] (Figure 5) As a resource centre, it provides space for a wide range of community services and activities, including classrooms, youth group rooms, a main hall and a pottery room.[97] The location, close to the University of Edinburgh, attracts many students and staff, making it an important centre for Edinburgh's festivals and events.[98] The richness of the surrounding environment, with its proximity to Dovecot Studios, Blackwells Bookshop and the Edinburgh Institute for Climate Change, creates a diverse area of cultural, retail, residential and educational functions, with easy access to the city for both residents and tourists to visit.[99] In terms of sustainability, the design solution emphasises the building's energy efficiency, focuses on the durability and ease of maintenance of structural elements and systems, and selects breathable and energy-efficient materials and designs to ensure that the building is used in a way that effectively reduces its environmental impact. In addition, the design programme follows the guidelines of the City of Edinburgh Plan 2030 and Scotland's National Planning Framework 4 (NPF4), demonstrating a commitment to sustainability and ensuring that the building meets the requirements of environmental protection and social responsibility in its future use.[100]

Figure 4, "South Bridge Resource and Education Centre Location Information (Red Block)," City of Edinburgh Council, https://citydev-portal.edinburgh.gov.uk/idoxpa-web/files/674A86B91055CF4BCD1D777F742E3F85/pdf/24_02998_FUL-DESIGN_AND_ACCESS_STATEMENT_PART_ONE-6342318.pdf.

Figure 5, "South Bridge Resource and Education Centre Street View Photos on Infirmary Street," City of Edinburgh Council, https://citydev-portal.edinburgh.gov.uk/idoxpa-web/files/674A86B91055CF4BCD1D777F742E3F85/pdf/24_02998_FUL-DESIGN_AND_ACCESS_STATEMENT_PART_ONE-6342318.pdf.

95 Edinburgh Festival Fringe Society Ltd. 6 Infirmary Street, Edinburgh Design & Access Statement Part one. Edinburgh: Studio LBA, 2023. https://citydev-portal.edinburgh.gov.uk/idoxpa-web/files/674A86B91055CF4BCD1D777F742E3F85/pdf/24_02998_FUL-DESIGN_AND_ACCESS_STATEMENT_PART_ONE-6342318.pdf
96 Ibid.
97 Ibid.
98 Ibid.
99 Ibid.
100 Edinburgh Festival Fringe Society Ltd. 6 Infirmary Street, Edinburgh Design & Access Statement Part Three. Edinburgh: Studio LBA, 2023. https://citydev-portal.edinburgh.gov.uk/idoxpa-web/files/C4D5311D171CFE0CB818BDA1171F8F60/pdf/24_02998_FUL-DESIGN_AND_ACCESS_STATEMENT_PART_THREE-6342319.pdf f

Case Study 2 - Multi-purpose commercial space

The Jenners Building, located at 47-52 Princes Street in Edinburgh city centre, is a historically important Category A listed building built in 1895.[101] (Figure 6) The building is situated on Princes Street in the centre of Edinburgh, surrounded by a thriving commercial and cultural environment, and the area is well served by public transport, including buses and trams, making it easily accessible to both locals and visitors. Jenners was originally established as a department store in 1838, the existing building was designed by William Hamilton Beatty and reopened in 1895 after the original building was destroyed by fire, it was built in an ornate renaissance revival style, adorned with columns and balustrades, (Figure 7) Jenners operates as a department store until 2020 and is now being refurbished with plans to convert it into a hotel and retail space.[102](Figure 8) The building was acquired by AAA United in 2017 and a major restoration programme has subsequently commenced to retain its historical and architectural significance whilst introducing modern amenities.[103] The conversion programme includes a premium hotel with approximately 100 rooms, restaurants, cafes and retail space, a three-storey central atrium that will be restored to its former glory and new infrastructure that will be sensitively integrated.[104] The refurbishment was led by David Chipperfield Architects in collaboration with 3DReid and Loader Montieth Architectural Studio, with construction company GRAHAM responsible for the main and core works, and the project team worked closely with Historic Environment Scotland and the City of Edinburgh Council to ensure the restoration was sensitive.[105] The sustainability of the building materials was achieved through a series of measures during the renovation of the building, including the selection of low embodied carbon and highly recycled materials, the retention of the existing structure to reduce the need for new materials and carbon emissions, the restoration and reuse of historic materials, the conduct of a detailed structural survey to maximise the use of existing materials and the removal of inappropriate alterations to restore the building to its original condition.[106] These measures not only reduce resource consumption and carbon footprint, but also preserve the historic value of the building, demonstrating the developer's focus on and responsibility for sustainability.[107]

Figure 6, "The Jenners Building Location Information (Red Block)," Jenners Building, "Design and Access Statement Part 1," https://static1.squarespace.com/static/619e2b7e64538a287305903a/t/61f2f752c012570030b2201d/1643313021725/Jenners+Building+Design+and+Access+Statement+part-1.pdf.

101 "History," The Jenners Building, https://www.thejenners building.com/jenners-building-history.

102 Ibid.

103 Edinburgh Architecture. "Edinburgh Centre for Carbon Innovation." https://www.edinburgharchitecture.co.uk/edinburgh-centre-carbon-innovation.

104 Ibid.

105 Lizzie Crook, "David Chipperfield Architects to Revamp Jenners Store in Edinburgh," Dezeen, February 2, 2022, https://www.dezeen.com/2022/02/02/david-chipperfield-jenners-department-store-renovation/.

106 Jenners Building, "Design and Access Statement Part 1," https://static1.squarespace.com/static/619e2b7e64538a287305903a/t/61f2f752c012570030b2201d/1643313021725/Jenners+Building+Design+and+Access+Statement+part-1.pdf.

107 Ibid.

Jenners ca. 1870

Jenners Department Store Fire ca. 1892

1895
© Courtesy of HES (Bedford Lemere and Company Collection)

2021

Figure 7, "The Jenners Building History Photos," Jenners Building, "Design and Access Statement Part 1," https://static1.squarespace.com/static/619e2b7e64538a287305903a/t/61f2f752c012570030b2201d/1643313021725/Jenners+Building+Design+and+Access+Statement+part-1.pdf.

Figure 8, "The Jenners Building undergoing renovation", photo by the author.

Case Study 3 - Multi-purpose small buildings (former residential)

Holyrood Park Lodge is located at the entrance of Edinburgh's Holyrood Park, one of the park's four main entrances, at the eastern end of the parliamentary area, EH8 8AZ.[108] (Figure 9) Its buildings and surroundings are listed as a conservation site of Holyrood Park, along with the Palace of Holyroodhouse and the Scottish Parliament building.[109] It is a Victorian style building, classified as a Category B listed building, which was built in 1857 and designed by Scottish engineer Robert Matheson, with distinctive external features such as diamond-shaped chimneys and decorative curved edges.[110] (Figure 10) The lodge was originally built for the Royal Parks keepers and later also used by the Royal Parks Police and from 2017 Holyrood Park Lodge is being used as an information centre for visitors to Holyrood Park and as an educational space for commercial activities within the park such as event management and car parking.[111] The restoration and upgrade of the lodge aimed to improve the thermal performance of the building whilst maintaining its historic character and appearance, the restoration process used appropriate materials to minimise disruption to the original fabric and reinstated some of the traditional decorative detailing to enhance the overall aesthetics and functionality of the building.[112] The retrofit measures, which included internal insulation with cellulose materials, double-glazed windows and roof insulation with wood fibre boards, have significantly improved the building's energy efficiency and reduced carbon emissions.[113]

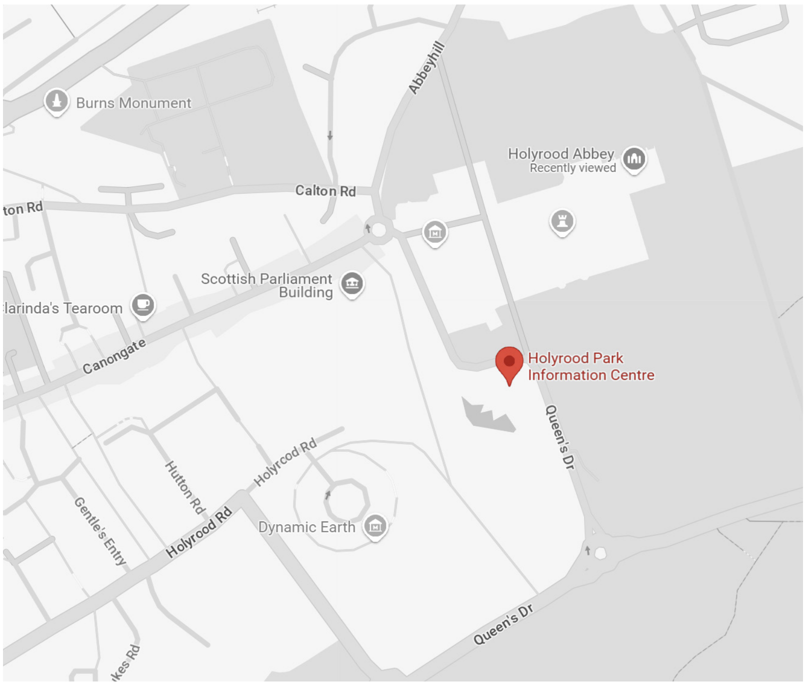


Figure 9, "Holyrood Park Lodge loaction", image from Google map,Secondary processing by authors

Figure 10, "Holyrood Park Lodge Street View," image courtesy of HiBERATLAS, https://hiberatlas.eurac.edu/en/holyrood-park-lodge--2-120.html."

108 Historic Environment Scotland, "Refurbishment Case Study 37: Holyrood Park Lodge, Edinburgh: Thermal Upgrade Works to a 19th Century Lodge House, https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f7c8b362-f78b-416a-9733-abb5009c521d.
109 Ibid.
110 Ibid.
111 Ibid.
112 Historic Environment Scotland, "Refurbishment Case Study 37: Holyrood Park Lodge, Edinburgh: Thermal Upgrade Works to a 19th Century Lodge House," https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f7c8b362-f78b-416a-9733-abb5009c521d.
113 Ibid.

The research used the entropy weighting method and linear weighting method to scientifically analyse the impact of various indicators of the wall on the sustainable renovation of historic buildings. Entropy weighting is a multi-attribute decision-making method based on information entropy, which determines the weights by calculating the information entropy of each attribute, and has the advantages of objectivity and adaptability, but relies on high-quality data and is complicated to calculate.[114] Linear weighting method assigns fixed weights to each attribute and makes linear combinations to make decisions, which is simple, easy to use and flexible, but the determination of weights is highly subjective and ignores the interaction between attributes.[115]

The study will also calculate the U-values of the walls and use the analysis to judge the thermal performance of the facades of the three historic buildings. The U-value (heat transfer coefficient) of a wall is an important indicator of a building's heat transfer performance and the lower the U-value, the better the insulation performance of the wall.[116] The formula for calculating the value of U is given by:

$$U = \frac{1}{RT}$$

Where Rt is the total thermal resistance of all materials, calculated as[117]:

$$R_t = R_{si} + \sum_{i=1}^{n} R_i + R_{se}$$

The thermal resistance of each layer of material is[118]:

$$R = \frac{D}{\lambda}$$

D is the thickness of the material and λ is the thermal conductivity of the material[119]

R_si is units of thermal resistance of thin layers of air on indoor surfaces (R_si=0.12)[120]

R_se is the unit of air thin layer thermal resistance for outdoor surfaces (R_se=0.06)[121]

114 Zhu, Yuxin, Dazuo Tian, and Feng Yan. "Effectiveness of Entropy Weight Method in Decision-Making." Mathematical Problems in Engineering 2020 (2020): 3564835. https://doi.org/10.1155/2020/3564835.
115 Kazak, Ekaterina, Yifan Li, Ingmar Nolte, and Sandra Nolte (Lechner). "A Linear Weight Estimator for Dynamic Global Minimum Variance Portfolio Allocation." October 25, 2023. Available at SSRN: https://ssrn.com/abstract=4011298 or http://dx.doi.org/10.2139/ssrn.4011298.
116 Franco, José Tomás. "How to Calculate the U-Value of a Building's Exterior Wall?" ArchDaily. August 2, 2018. https://www.archdaily.cn/cn/899261/zen-yang-ji-suan-jian-zhu-wai-qiang-de-chuan-re-xi-shu-uzhi.
117 Ibid.
118 Ibid.
119 Ibid.
120 Ibid.
121 Ibid.

Life Cycle Assessment (LCA) plays an important role in the sustainability of historic buildings by comprehensively assessing the environmental impacts of buildings throughout their lifecycle, facilitating the reuse of materials, supporting policy development, optimising design choices and integrating multiple impacts.[122] LCA not only helps to identify and quantify carbon emissions and resource consumption, but also provides designers and policy makers with the scientific basis to make more sustainable decisions while preserving historic buildings, resulting in significant reductions in carbon emissions and improved environmental performance of buildings.[123] Through assessing the 'embodied impacts' of building materials, such as during production, transport, construction and dismantling, designers can gain a more comprehensive understanding of a building's environmental burden and make more sustainable choices at the design stage.[124] The strength of LCA lies in its comprehensiveness and data-driven decision support, which can reveal the long-term environmental impacts of material choices.[125] Overall, LCA provides an important tool and methodology for sustainable building design, helping designers and decision makers to optimise building design and reduce environmental burdens.[126]

The calculations for LCA are taken from 'Design Guidance for Data-Driven LCA Based Design Methods and Tool Prototyping' by Thomas Jusselme et al, 2019. Calculating the impact of a building's life cycle can be done by adding up the operational and embodied impacts, which can be expressed in formula 1. In the formula 1, 'IBLC' (Building Life Cycle Impact) is the environmental impact of the building over its entire life cycle, 'IOP' (operational impacts) is the energy consumed, and environmental impacts generated during the use phase of the building, 'IEM' (embodied impacts) refers to the environmental impacts generated by the building during the production, transport and construction phases. [127]

$$I_{BLC} = I_{OP} + I_{EM}$$

Formula 1

The IOP (Impact of Operation) is calculated by disaggregating the energy demand of a building into different types of energy (e.g. biomass or natural gas) and calculating them in hourly time steps over the entire life cycle of the building, it can be expressed as formula 2.[128] In the formula 2, Ek stands for energy demand and CFk is a specific environmental impact conversion factor provided by the KBOB database, which serves to convert the energy demand into an environmental impact factor. LB stands for the lifetime of the building and SB stands for the surface area of the building.[129]

$$I_{OP} = \frac{\sum_{k=1}^{p} E_k \cdot CF_k}{LB \times SB}$$

Formula 2

122 Farzaneh Karimi et al., "A Systematic Review of Sustainability Rating Systems for Historic Buildings," Sustainability 14, no. 19 (2022): 12448, https://doi.org/10.3390/su141912448.
123 Ibid.
124 Thomas Jusselme et al., "Design Guidance from a Data-Driven LCA-Based Design Method and Tool Prototype," Proceedings of Building Simulation 2019: 16th Conference of IBPSA, 2019, https://publications.ibpsa.org/proceedings/bs/2019/papers/BS2019_210403.pdf.
125 Ibid.
126 Ibid.
127 Ibid
128 Ibid.
129 Ibid.

To calculate the IEM (embodied impact), the building is firstly divided into components (e.g. insulation, heating equipment, etc.), each of which is expressed in terms of mass (kg), surface area (m²), or quantity (units), which can be denoted as mi.[130] Secondly, each of these components has a conversion factor for its environmental impact, denoted as CFi, it is used to convert the physical quantity of the component (e.g. mass or area) into its environmental impact.[131] Then, the lifetime of the building (LB) and the lifetime of each component (LMi) are considered, and these factors are integrated to calculate the environmental impact over the entire life cycle of the building.[132] The final value obtained is divided by the floor area and life of the building to get the final embodied impacts.[133]

$$I_{EM} = \frac{\sum_{i=1}^{n} m_i \cdot CF_i \cdot \left[\frac{LB}{LM_i}\right]}{LB \times SB}$$

Formula 3

Given the challenges of data acquisition and computational complexity, this study employs EcoTool, a sustainability assessment tool grounded in the Life Cycle Assessment (LCA) methodology. EcoTool evaluates the sustainability of historic buildings by analyzing envi-ronmental impacts, energy consumption, and greenhouse gas emissions.[134] It facilitates the estimation of a building project's ecological footprint using minimal input data, leveraging Swiss-approved standards such as SIA and KBOB for balanced calculations.[135] This software is particularly suitable during the pre-design phase, where it enables rapid estimation of a building project's lifecycle environmental impact, thereby minimizing potential environmental harm.[136]

Sustainability analyses using EcoTool commence with the collection of comprehensive material data, including detailed information on building materials and project background. The collected data is entered into EcoTool, which conducts a Life Cycle Inventory (LCI) to quantify resource consumption and environmental emissions throughout the building's lifecycle. EcoTool processes the inventory data to generate environmental impact indicators, providing a detailed breakdown of a building's ecological performance. The LCA report generated by EcoTool offers a comprehensive analysis of the environmental impact of historic building materials over their lifecycle. It identifies materials with the highest envi-ronmental impact, enabling the selection of low-carbon, sustainable alternatives. This process not only reduces the carbon footprint of historic buildings but also enhances their environmental performance while maintaining their historical integrity.

This research focuses on the wall structures and materials utilized following retrofitting, with the aim of investigating how these materials influence the overall performance, sustainability, and cultural value of historic buildings. By examining three retrofitted historic buildings in Edinburgh, this study investigates changes in wall structures, documents the physical properties and environmental impacts of the materials used, and analyses the influence of these materials on retrofitting outcomes. This comprehensive analysis underscores the critical role that material selection plays in achieving conservation and sustainability goals for historic buildings.

The selected case studies provide diverse contexts for exploring the relationship between material properties, environmental performance, and cultural value. By documenting the physical and environmental characteristics of the materials applied during retrofitting, the study sheds light on how these materials contribute to the durability, energy efficiency, and heritage preservation of historic buildings. The analysis highlights not only the technical performance of materials but also their capacity to meet the dual demands of preserving cultural heritage and enhancing

130 Ibid.
131 Ibid.
132 Ibid.
133 Ibid.
134 "Was ist das EcoTool?" EcoTool, https://ecotool.org/de/dokumentation/was-ist-das-ecotool.
135 Ibid.
136 Ibid.

environmental sustainability.

Drawing on these findings, the research provides targeted recommendations for material selection in future renovation projects. These recommendations advocate for adopting renovation practices that balance historical preservation with modern sustainability requirements. By promoting the use of materials that align with both historical authenticity and environmental performance, the study offers actionable insights for advancing renovation strategies that cater to both traditional and contemporary needs. Ultimately, this research emphasizes the importance of a holistic approach to material selection, ensuring that future renovation projects uphold the cultural and historical significance of historic buildings while addressing the environmental challenges of the modern era.

Results

Project name	Wall structure layers from outside to inside	Total thickness of wall
South Bridge Resource and Education Centre	Existing Stone Brick- rubble and ashlar 550mm T&G V-Jointed Lining Boards 20mm Cavities and timber frames 25mm Plasterboard 13mm Hemp indi-therm 100mm Rigid insulation 60mm Breathable plaster 40mm Existing plaster 20mm	828mm
Holyrood Park Lodge	Stone Brick- rubble and ashlar 550mm Cellulose Fiber Insulation 40mm Lime plaster on a framework of wooden laths 25mm	615mm
The Jenners Building	Existing Stone Brick- rubble and ashlar 550mm Timber board 20mm Rockwool Insulation 50mm polystyrene board 100mm Breathable plaster 10mm plaster board 20mm	750mm

Table 1, Description of wall construction

The data in the table is taken from the alteration plans (Design and Access Statements) submitted by the design team to the City of Edinburgh Council and the completed Alterations Report.

In the cases of the South Bridge Resource and Education Centre (Figure 11), The Jenners Building (Figure 12), and Holyrood Park Lodge (Figure 13), the facades have been adapted from their original historic designs, retaining stone cladding to preserve historical features while integrating modern architectural concepts. Both the South Bridge Resource and Education Centre and The Jenners Building utilize Framed Wall Construction methods. While both constructions include wall cavities, The Jenners Building incorporated insulation within the cavities, whereas the South Bridge Resource and Education Centre did not. Despite this, the South Bridge Resource and Education Centre exhibits a significantly lower wall U-value compared to The Jenners Building. This improved thermal performance is attributed to the Centre's thicker insulation and ad-ditional design layers, which effectively minimize heat transfer and significantly enhance energy efficiency.

In contrast, Holyrood Park Lodge employs Non-Framed Wall Construction, which also fea-tures stone as the outermost material. This design relies on solid walls to bear loads directly, offering structural simplicity. This approach enables a more efficient retrofitting process, with advantages in manufacturing costs and reduced construction time, particularly for low-rise buildings. However, the reliance on solid walls and the lack of additional insulating layers result in slightly lower thermal performance compared to the other two buildings. Overall, the comparison of these three retrofitted historic buildings demonstrates the importance of tailored retrofitting strategies that consider the specific structural and material characteristics of each building. The findings highlight the trade-offs between thermal performance, struc-tural efficiency, and construction practicality, providing valuable insights for the sustainable renovation of historic buildings.

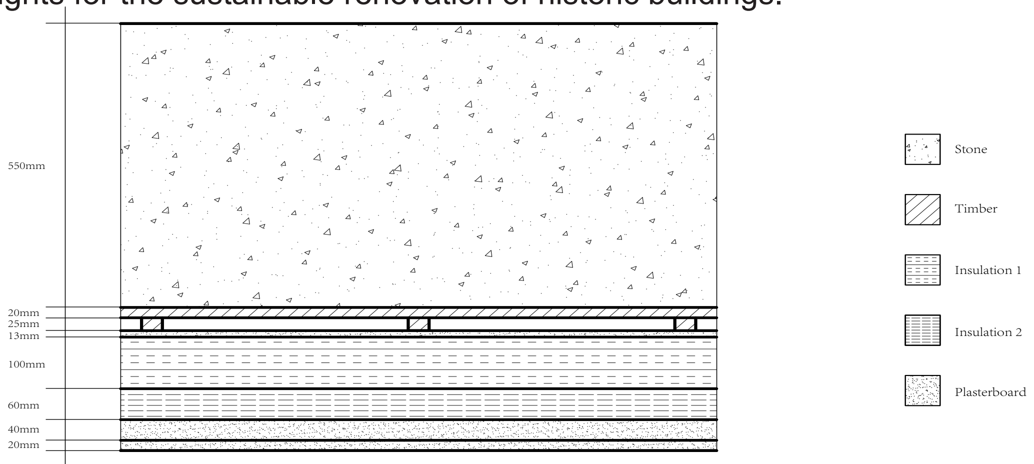


Figure 11, 'South Bridge Resource and Education Centre Projected retrofitted wall structure', Images processed and drawn by the author, data from DESIGN_AND_ACCESS_STATEMENT submitted by the design team to Edinburgh Council. https://static1.squarespace.com/static/619e2b7e64538a287305903a/t/61f2f752c012570030b2201d/1643313021725/Jenners+Building+Design+and+Access+Statement+part-1.pdf.

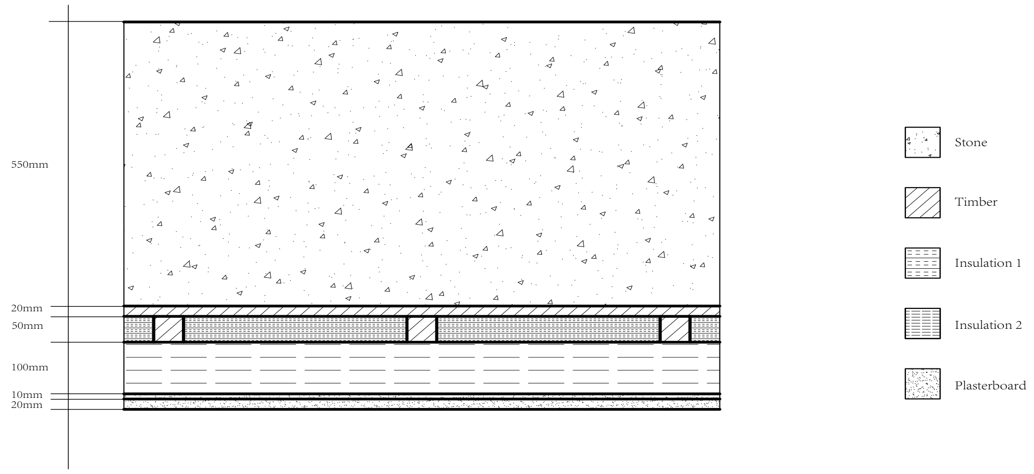


Figure 12, 'The Jenners Buildingre Projected retrofitted wall structure',Images processed and drawn by the author, data from DESIGN_AND_ACCESS_STATEMENT submitted by the design team to Edinburgh Council. https://static1.squarespace.com/static/619e2b7e64538a287305903a/t/61f2f752c012570030b2201d/1643313021725/Jenners+Building+Design+and+Access+Statement+part-1.pdf.

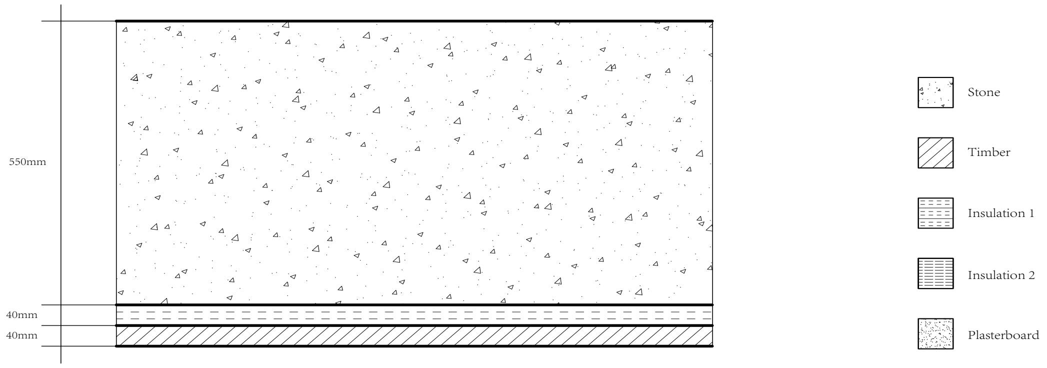


Figure 13, 'Holyrood Park Lodge remodelled wall structure', Images were processed and drawn by the authors, and data were derived from available alteration reports.' https://www.historicenvironment.scot/archives-and-research/publications/publication/?publicationId=f7c8b362-f78b-416a-9733-abb5009c521d.

Project Name	Factors	Indicators
South Bridge Resource and Education Centre	U - values (W/m2.K)	0.21
	GHG (kgco 2 -eq/m2/a)	1.70
	gray energy (kWh/m2/a)	7.40
	UBP(UBP/m2/a)	3382.00
	NUMBER OF LAYER	8.00
	U VALUE Difference before and after alteration	1.39
Holyrood Park Lodge	U - values (W/m2·K)	0.67
	GHG (kgco 2 -eq/m2/a)	0.70
	gray energy (kWh/m2/a)	3.00
	UBP(UBP/m2/a)	1531.00
	NUMBER OF LAYER	4.00
	U VALUE Difference before and after alteration	0.63
The Jenners Building	U - values (W/m2·K)	0.30
	GHG (kgco 2 -eq/m2/a)	2.20
	gray energy (kWh/m2/a)	9.40
	UBP(UBP/m2/a)	4424.00
	NUMBER OF LAYER	7.00
	U VALUE Difference before and after alteration	1.00

Table 2, Project wall data, calculated using Ecotool and the wall U-Value table.

A combined entropy weighting and linear weighting methodology was used to develop a robust assessment framework for evaluating the wall structures of three buildings: South Bridge Resource and Education Centre, Holyrood Park Lodge, and The Jenners Building. The entropy weighting method assigns weights to performance indicators, such as U-value, greenhouse gas emissions, and grey energy, ensuring an unbiased and equitable assessment. By applying data normalization and entropy calculations, this method reflects the relative significance of each indicator in contributing to overall building performance. The linear weighting method complements the entropy approach by applying the calculated weights to actual performance values, producing a comparable composite score for each wall configuration. This scoring system allows for a standardized evaluation across multi-dimensional criteria, ensuring that results are both consistent and actionable. These methods effectively integrate diverse datasets, providing a comprehensive foundation for sustainability evaluations.

This comprehensive approach provides practical guidance for selecting the optimal wall structure in a refurbishment project. By prioritising wall constructions with a higher composite score, decision makers can achieve a balance between environmental and economic benefits. For example, configurations that minimise U-values while reducing greenhouse gas emissions and grey energy consumption not only improve thermal performance but also align with long-term sustainability goals. This science-based assessment ensures that renovation practices contribute to the dual goals of improving energy efficiency and preserving historic integrity. Ultimately, the combination of the entropy and linear weight methods provides practitioners with a reliable tool for assessing the sustainability of building wall structures. This approach emphasises the importance of data-driven decision-making in achieving environmentally and economically viable refurbishment outcomes, which are important for the sustainable conservation of historic buildings.

STEPS		CASE		FACTORS						SCORE
entropy weighting										
CODE				U - values (W/m2·K)	GHG (kgco 2 -eq/m2/a)	gray energy (kWh/m2/a)	UBP(UBP/m2/a)	NUMBER OF LAYER	U VALUE Difference before and after alteration	
			TYPE	-	-	-	-	+	+	
	1	South Bridge Resource and Education Centre		0.21	1.70	7.40	3382.00	8.00	1.39	
	2	Holyrood Park Lodge		0.67	0.70	3.00	1531.00	4.00	0.63	
	3	The Jenners Building		0.30	2.20	9.40	4424.00	7.00	1.00	
			MAX	0.67	2.20	9.40	4424.00	8.00	1.39	
			MIN	0.21	0.70	3.00	1531.00	4.00	0.63	
			DIV	0.46	1.50	6.40	2893.00	4.00	0.76	
standard value		South Bridge Resource and Education Centre		1.00	0.33	0.31	0.36	1.00	1.00	
		Holyrood Park Lodge		0.00	1.00	1.00	1.00	0.00	0.00	
		The Jenners Building		0.80	0.00	0.00	0.00	0.75	0.49	
panning		South Bridge Resource and Education Centre		1.10	0.43	0.41	0.46	1.10	1.10	
		Holyrood Park Lodge		0.10	1.10	1.10	1.10	0.10	0.10	
		The Jenners Building		0.90	0.10	0.10	0.10	0.85	0.59	
pij		South Bridge Resource and Education Centre		0.52	0.27	0.26	0.28	0.54	0.62	
		Holyrood Park Lodge		0.05	0.67	0.68	0.66	0.05	0.06	
		The Jenners Building		0.43	0.06	0.06	0.06	0.41	0.33	
K			-0.91							
ej				0.77	0.72	0.71	0.73	0.77	0.75	
gj				0.23	0.28	0.29	0.27	0.23	0.25	
w				0.15	0.18	0.19	0.18	0.15	0.16	
linear weighting scheme										
		South Bridge Resource and Education Centre		0.15	0.06	0.06	0.06	0.15	0.16	0.64
		Holyrood Park Lodge		0.00	0.18	0.19	0.18	0.00	0.00	0.54
		The Jenners Building		0.12	0.00	0.00	0.00	0.11	0.08	0.31

Table 3, scores calculated by entropy weighting and linear weighting for 3 cases

The table shows data from three retrofitted buildings, focusing on how their wall retrofits improved sustainability. Key metrics like U-value, greenhouse gas emissions, and grey energy were compared using a linear weighting method. Among the three, the South Bridge Resource and Education Centre performed best, showing clear improvements in building performance and sustainability. The U-value measures how much heat passes through a wall; lower U-values mean better insulation and lower energy use for heating or cooling. This makes it a key indicator of insulation quality and energy efficiency. Comparing U-values before and after retrofitting helps judge the success of the improvements.

The South Bridge Resource and Education Centre achieved the lowest U-value of 0.21 W/m²K, showing the best insulation. Holyrood Park Lodge had the highest U-value at 0.67 W/m²K, indicating the weakest insulation. The South Bridge Centre also showed the biggest improvement, with a U-value reduction of 1.39 W/m²K, while Holyrood Park Lodge had the smallest drop, only 0.63 W/m²K. The Jenners Building had moderate results, lowering its U-value by 1.0 W/m²K to meet local standards at 0.3 W/m²K. These results show how important it is to customize retrofitting strategies to improve insulation and energy efficiency while preserving historical features.

Greenhouse gas (GHG) emissions and grey energy are also key for judging a building's environmental impact. Lower values for both mean the building is more sustainable and has less impact on the environment. GHG emissions represent gases released during energy use, measured as carbon dioxide equivalent (CO_2e). Grey energy is the energy used to produce, transport, and build materials. Lower grey energy values mean better resource use, while higher ones show a bigger environmental cost. This study focused only on the single walls of these retrofitted buildings. Among the three, Holyrood Park Lodge performed best in reducing GHG emissions and grey energy, while the Jenners Building had the worst results.

Unit Building Performance (UBP) measures energy use and environmental impact per unit of area or volume. This study looked only at parts of walls, not entire buildings. Taller buildings tend to have better thermal insulation because of their wall designs, improving energy efficiency. A composite score was calculated by giving different weights to U-value, GHG emissions, and grey energy. Higher scores mean better alignment with sustainability goals. This study shows the value of combining these metrics to assess retrofitted historic buildings and achieve meaningful environmental and energy efficiency improvements.

Discussion

By studying the wall structures of the South Bridge Resource and Education Centre, Holyrood Park Lodge, and The Jenners Building, we found that wall material and thickness play a key role in energy efficiency and overall performance. Modern building technology has made it possible to improve energy use and comfort in historical buildings while preserving their cultural and historical value. Future wall renovation strategies should carefully balance modern functional needs with historical preservation.

For optimal results, wall thickness should be kept between 600 mm and 800 mm. This range provides good insulation, saves space, and supports both exterior design and interior functionality. The insulation layer is crucial, with a minimum thickness of 100 mm recommended for basic performance. For commercial buildings prioritizing energy efficiency, insulation up to 140 mm is ideal. Gypsum board, known for its fire resistance and durability, should be between 12.5 mm and 15 mm thick. Together, the insulation and gypsum board should have a total thickness of 140 mm to 150 mm. Brick walls should make up 30% to 50% of the structure to ensure stability and durability, especially for facades and partitions in commercial buildings.

In addition to material and thickness, renovations should address air circulation and humidity control. Improving energy efficiency also means maintaining good indoor air quality. Proper wall design can reduce moisture and prevent mold, creating a healthier indoor environment. Using permeable materials and ventilation systems helps regulate humidity and protects the structure from damage. Modern techniques like thermal bridge treatment and airtight construction can further boost energy performance.

For aesthetics and cultural preservation, material choices must align with the building's original style and cultural significance. Using materials that match historical and regional characteristics protects the building's heritage while enhancing its appearance. For facades, sustainable and locally sourced materials are recommended to lower environmental impact. Preserving and showcasing the historical features strengthens emotional connections for users and helps maintain cultural heritage for future generations.

Figure 14 is a summary of the wall structure based on the discussion.

Conclusion

This study gives simple advice on improving the walls of the Southbridge Resource and Education Centre, Holyrood Park Lodge, and Janus House. It explains how to make these historic buildings more energy-efficient while keeping their original style. The study highlights the importance of using suitable materials and proper wall thickness to save energy and support sustainable renovations.

The study uses scientific methods to measure environmental impact with indicators like U-values, greenhouse gas emissions, and grey energy. These results can help policymakers make better green building plans. It also raises awareness about protecting historic buildings and improving their energy efficiency. The study provides ideas for future projects and encourages communities to take part in heritage preservation and sustainability.

However, it still has some limits. The focus now is only at one wall section, which may not reflect the full performance of the buildings. Future research could include more parts of the structures. The calculations depend on data processing, which could cause errors if done poorly. Improving these methods and trying new ones could reduce mistakes. The study also mentionedn wall thickness and thermal performance but did not examine how different materials affect sustainability. Studying this could lead to better advice for redesigning more sustainable buidlings.

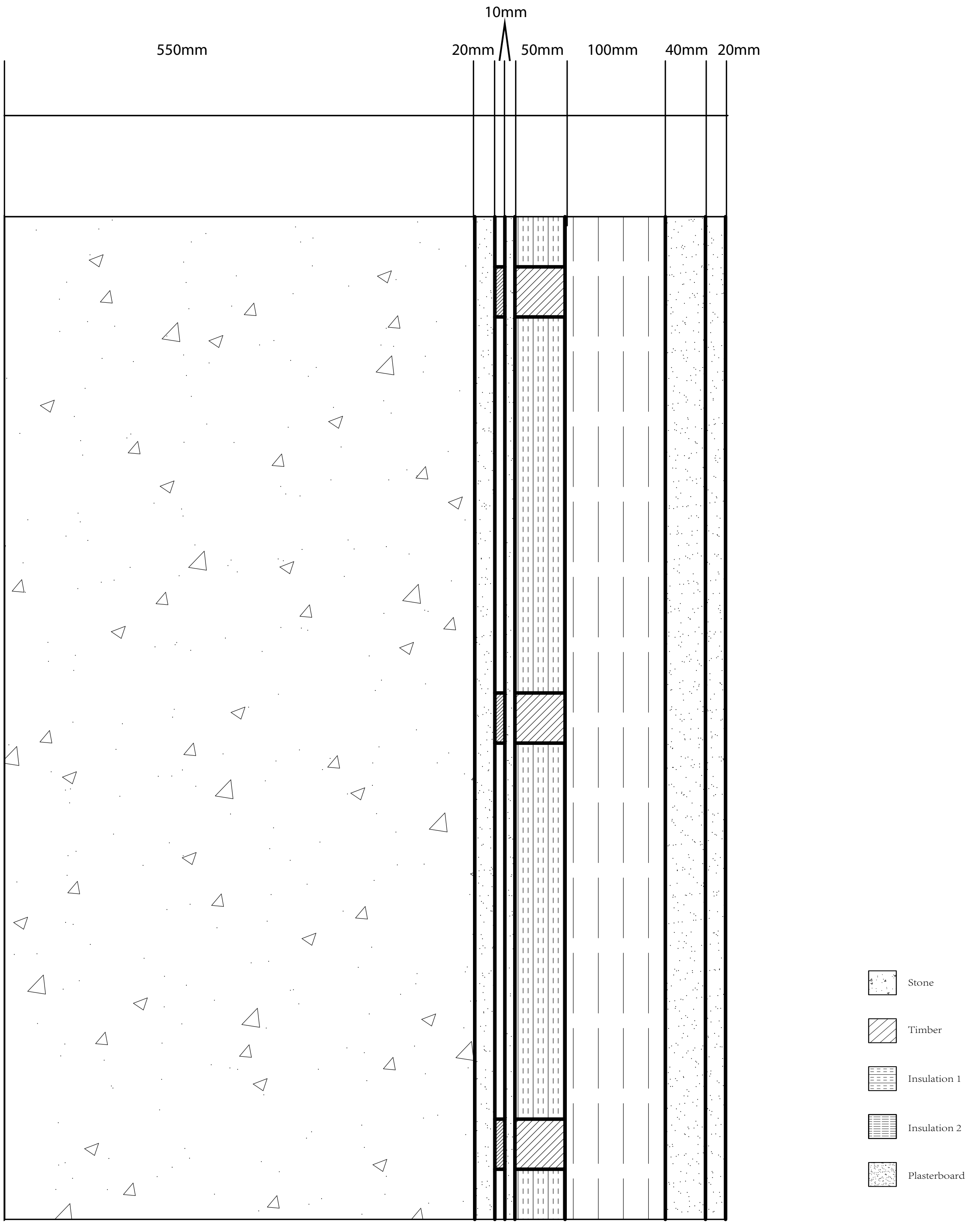


Figure 14, Typical case wall construction based on discussions

Bibliography

Abed, Joseph, Scott Rayburg, John Rodwell, and Melissa Neave. "A Review of the Performance and Benefits of Mass Timber as an Alternative to Concrete and Steel for Improving the Sustainability of Structures." Sustainability 14, no. 9 (2022): 5570.

Bashirzadeh Tabrizi, Toktam et al. "The Impact of Different Insulation Options on the Life Cycle Energy Demands of a Hypothetical Residential Building." Procedia Engineering (2017), n.p.

Bullen, Peter A., and Peter E.D. Love. "Adaptive Reuse of Heritage Buildings." Structural Survey 29, no. 5 (2011): 411-421.

Cecere, Carlo, Michele Morganti, and Gianluca Mortarotti. "Thermal Analysis and Energy-Efficient Solutions to Preserve Listed Building Façades: The INA-Casa Building Heritage." Buildings 7, no. 3 (2017): 56.

Choudhary, Shweta, Satish Pipralia, and Nand Kumar. "Need for Integrated Approach for Energy Efficiency Assessments and Material Evaluation of Historic Buildings." Materials Today: Proceedings 42, no. 4 (2021): 1727-1731.

City of Edinburgh Council. Listed Buildings and Conservation Areas Guidance. 2022.

Crook, Lizzie. "David Chipperfield Architects to Revamp Jenners Store in Edinburgh." Dezeen, February 2, 2022.

Edinburgh Festival Fringe Society Ltd. 6 Infirmary Street, Edinburgh Design & Access Statement Part one. Edinburgh: Studio LBA, 2023.

Edinburgh Festival Fringe Society Ltd. 6 Infirmary Street, Edinburgh Design & Access Statement Part Three. Edinburgh: Studio LBA, 2023.

Edinburgh World Heritage. “The UNESCO World Heritage Site.”

Historic England. "Energy Efficiency and Retrofit in Historic Buildings." Last modified July 31, 2024.

Historic England. "Properties of Traditional Building Construction."

Herrera-Avellanosa, Daniel et al. "Evaluating the Implementation of Energy Retrofits in Historic Buildings: A Demonstration of the Energy Conservation Potential and Lessons Learned for Upscaling." Heritage 7, no. 2 (2024): 997-1013.

IHBC. "Sustainability and Conservation of the Historic Built Environment." April 2020.

IPCC. Climate Change 2022: Mitigation of Climate Change. 2022.

IPCC. Climate Change 2022: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Sixth Assessment Report of the Intergovernmental Panel on Climate Change [H.-O. Pörtner, D.C. Roberts, M. Tignor, E.S. Poloczanska, K. Mintenbeck, A. Alegría, M. Craig, S. Langsdorf, S. Löschke, V. Möller, A. Okem, B. Rama (eds.)]. Cambridge University Press, Cambridge, UK and New York, NY, USA, 2022.

Jusselme, Thomas et al. "Design Guidance for Data-Driven LCA-Based Design Methods and Tool Prototyping." Proceedings of Building Simulation 2019: 16th Conference of IBPSA, 2019.

Karimi, F., N. Valibeig, G. Memarian, and A. Kamari. "Sustainability Rating Systems for Historic Buildings: A Systematic Review." Sustainability 14 (2022): 12448.

Kazak, Ekaterina, Yifan Li, Ingmar Nolte, and Sandra Nolte (Lechner). "A Linear Weight Estimator for Dynamic Global Minimum Variance Portfolio Allocation." SSRN: https://ssrn.com/abstract=4011298.

Kiviste, "Effect of Solar Radiation on Thermal Performance of External Wall Structures Based on Long-Term Measured Data." Tampere University, 2020.

Li, Yuan et al. "Research Frameworks, Methodologies, and Assessment Methods Concerning the Adaptive Reuse of Architectural Heritage: A Review." Built Heritage 5, Article number: 6 (2021).

Magrini, A., and A. Franco. "The Energy Performance Improvement of Historic Buildings and Their Environmental Sustainability Assessment." Journal of Cultural Heritage 21 (2016): 1-8.

Malz, Sebastian, Walter Krenkel, and Oliver Steffens. "Infrared Reflective Wall Paint in Buildings: Energy Saving Potentials and Thermal Comfort." Energy and Buildings 224 (2020): 110212.

Moldan, Bedřich, Svatava Janoušková, and Tomáš Hák. "How to Understand and Measure Environmental Sustainability: Indicators and Targets." Ecological Indicators 17 (2012): 4-13.

Odgaard, Tommy, Søren Peter Bjarløv, and Carsten Rode. "Interior Insulation - Experimental Investigation of Hygrothermal Conditions and Damage Evaluation of Solid Masonry Façades in a Listed Building." Building and Environment 129 (2018): 1-14.

Omer, Abdeen Mustafa. "Energy Consumption, Environment and Sustainable Development." Proceedings of the 3rd International Conference on Sustainable Energy and Environmental Protection (SEEP 2009), Dublin, 12-15 August 2009.

Pagoni, Panagiota, Eva Birgit Møller, Ruut Hannele Peuhkuri, and Nickolaj Feldt Jensen. "Evaluation of the Performance of Different Internal Insulation Systems in Real-Life Conditions—A Case Study." Building and Environment 267, Part C (2025): 112319.

Panakaduwa, Chamara, Paul Coates, and Mustapha Munir. "Identifying Sustainable Retrofit Challenges of Historical Buildings: A Systematic Review." Energy and Buildings 313 (2024): 114226.

Panico, Simone et al. "Long-term Monitoring Data of Hygrothermal Conditions of a Retrofitted Historic Building in Settequerce, South Tyrol (Italy)." Journal of Building Engineering 50 (2024): 104-118.

Panico, Simone et al. "Long-term Monitoring Data of Hygrothermal Conditions of a Retrofitted Historic Building in Settequerce, South Tyrol (Italy)." Building and Environment 129 (2018): 1-14.

Pezzey, John. Sustainable Development Concepts: An Economic Analysis. World Bank Environment Paper, no. 2. Washington, DC: The World Bank, 1992.

Porhinčák, Milan, and Adriana Eštoková. "Comparative Analysis of Environmental Performance of Building Materials Towards Sustainable Construction." Chemical Engineering Transactions 35 (2013): 1291-1296.
Pracchi, Valeria. "Historic Buildings and Energy Efficiency." The Historic Environment: Policy & Practice 5, no. 2 (2014): 210-225.

Reddy, B.V. Venkatarama. "Sustainable Materials for Low Carbon Buildings." International Journal of Low-Carbon Technologies 4, no. 3 (2009): 175-181.

RIBA. RIBA 2030 Climate Challenge Version 2. 2021.

RICS Research Trust. "The UN Sustainable Development Goals—a Common Language for Land, Construction and Real Estate."

Rivera-Lutap, Jocelyn A., Orlean G. Dela Cruz, Jhun M. Jacinto, Leslie Mae D. Vael, and Manuel M. Muhi. "Alternative Building Materials for a Sustainable Built Environment: A Literature Review." In Proceedings of the 10th International Conference on Energy Engineering and Environmental Engineering, 235-246. Springer, 2024.

Scottish Environment Protection Agency. "Historic Environment." In Our Environment. Accessed October 25, 2024.

Scottish Environment Scotland. "Scotland's Traditional Building Materials."

Tolou Del, Taher, Mohammad Sadegh, Bahram Saleh Sedghpour, and Sina Kamali Tabrizi. "The Semantic Conservation of Architectural Heritage: The Missing Values." Heritage Science 8, Article number: 70 (2020).

UNFCCC. 2023 Global Status Report for Buildings and Construction. 2023.

Vissilia, Anna-Maria, and Maria Villi. "Adobe and Timber Ties as Main Construction Materials for an Historic Greek Dwelling." International Journal of Architectural Heritage 4, no. 4 (2010): 295-319.

Wang, Guohao et al. "A Comprehensive Review of Building Lifecycle Carbon Emissions and Reduction Approaches." City and Built Environment 2, Article number: 12 (2024).

Woon, Kok Sin et al. "Recent Advances in Urban Green Energy Development Towards Carbon Emissions Neutrality." Energy 267 (2023): 126502.

Zeayter, Hoda, and Ashraf Mansour Habib Mansour. "Heritage Conservation Ideologies Analysis—Historic Urban Landscape Approach for a Mediterranean Historic City Case Study." HBRC Journal 14, no. 3 (2018): 345-356.

Zhu, Yuxin, Dazuo Tian, and Feng Yan. "Effectiveness of Entropy Weight Method in Decision-Making." Mathematical Problems in Engineering 2020 (2020): 3564835.

Appendix

TABLE 2a	Framed Wall Construction, U value through frame element.				
		Conductivity	Resistivity	Thickness	Resistance
List materials from inside to outside	Name of building material	K Value of material (W/mK)	r Value of material (mK/W)	material layer (m)	R value of element (m^2K/W)
surface resistance on internal face	OUTSIDE				0.12
building material 1	Existing Stone Brick- rubble and ashlar	3.500	0.286	0.550	0.16
building material 2	T&G V-Jointed Lining Boards	0.150	6.667	0.020	0.13
building material 3	Plasterboard	0.160	6.250	0.013	0.08
building material 4	Hemp indi-therm	0.060	16.667	0.100	1.67
building material 5	Rigid insulation	0.028	35.714	0.060	2.14
building material 6	Breathable plaster	0.200	5.000	0.040	0.20
building material 7	Existing plaster	0.160	6.250	0.020	0.13
building material 8					
building material 9					
building material 10					
surface resistance on external face					
if wall has a cavity*, enter surface resistance here				cavity 1	0.18
				cavity 2	
U value through building element	in W/m^2K				0.21
AND					

TABLE 2b	Framed wall construction, U value through cavity element.				
		Conductivity	Resistivity	Thickness	Resistance
List materials from inside to outside	Name of building material	K Value of material (W/mK)	r Value of material (mK/W)	material layer (m)	R value of element (m^2K/W)
surface resistance on external face	OUTSIDE				0.17
building material 1					0.00
building material 2					0.00
building material 3					0.00
building material 4					0.00
building material 5					0.00
building material 6					0.00
building material 7					0.00
building material 8					0.00
building material 9					0.00
building material 10					0.00
surface resistance on internal face	INSIDE				0.16
if wall has a cavity*, enter surface resistance here				cavity 1	
				cavity 2	
U value through building element	in W/m^2K				3.03
U Value through Framed Element			0.21	W/m^2K	
U Value through Cavity Element			3.03	W/m^2K	
width of Frame Element			0.80	m	
width of Cavity Element			0.00	m	
frame spacing			0.80	m	
Table 2a and 2b Combined U Value			**0.21**	W/m^2K	U-Value of Framed Wall Construction

U-value calculations for the South Bridge Resource and Education Centre

TABLE 2a	Framed Wall Construction, U value through frame element.				
		Conductivity	Resistivity	Thickness	Resistance
List materials from inside to outside	Name of building material	K Value of material (W/mK)	r Value of material (mK/W)	material layer (m)	R value of element (m^2K/W)
surface resistance on external face	OUTSIDE				0.12
building material 1	Existing Stone Brick- rubble and ashlar	3.500	0.286	0.550	0.16
building material 2	Timber board	0.150	6.667	0.020	0.13
building material 3	polystyrene board	0.035	28.571	0.100	2.86
building material 4	Breathable plaster	0.200	5.000	0.010	0.05
building material 5	plaster board	0.160	6.250	0.020	0.13
building material 6					
building material 7					
building material 8					
building material 9					0.00
building material 10					0.00
surface resistance on internal face	INSIDE				0.06
if wall has a cavity*, enter surface resistance here				cavity 1	0.18
				cavity 2	
U value through building element	in W/m^2K				0.27

AND

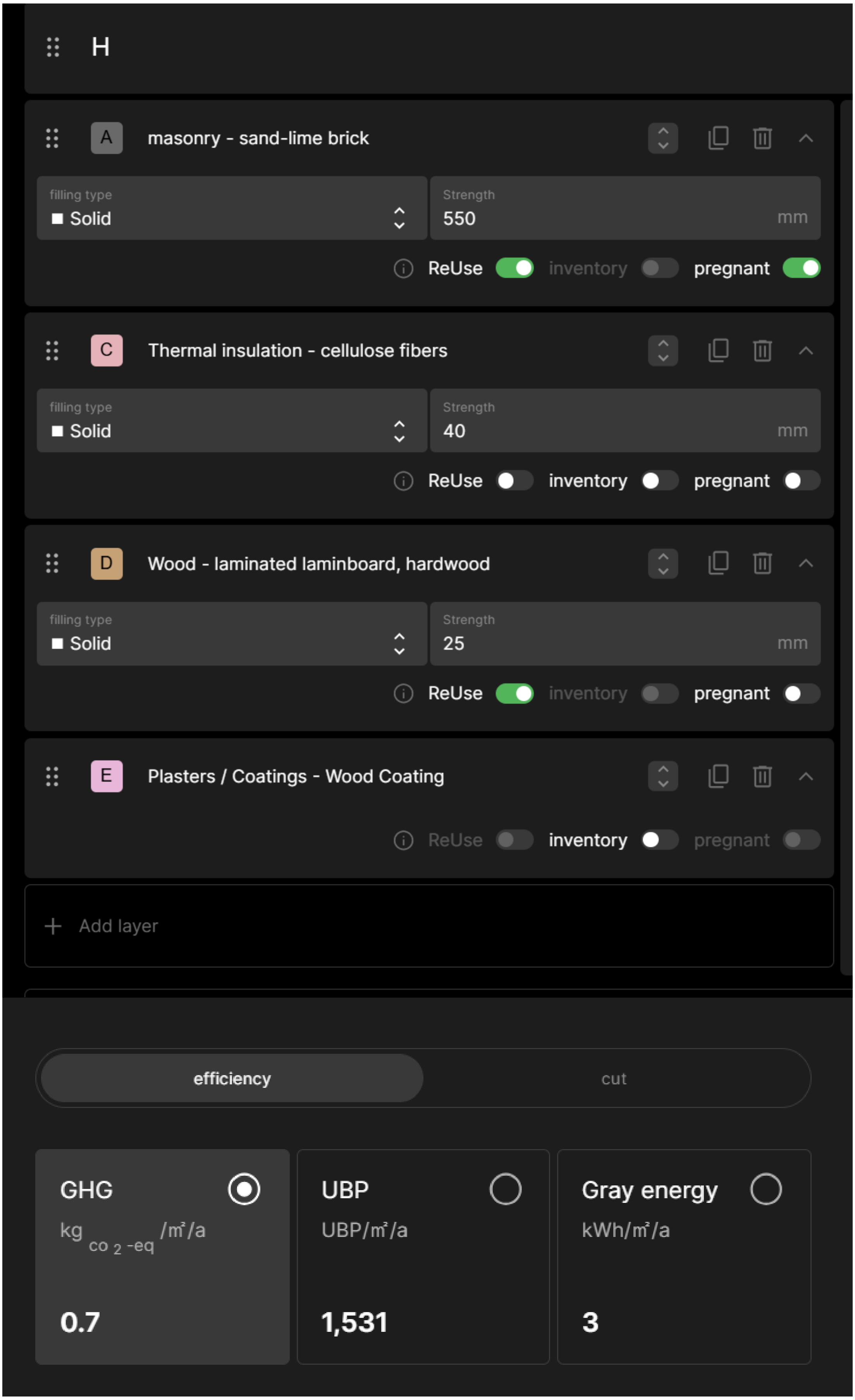
TABLE 2b	Framed wall construction, U value through cavity element.				
		Conductivity	Resistivity	Thickness	Resistance
List materials from inside to outside	Name of building material	K Value of material (W/mK)	r Value of material (mK/W)	material layer (m)	R value of element (m^2K/W)
surface resistance on external face	OUTSIDE				0.12
building material 1	Rockwool Insulation	0.040	25.000	0.050	1.25
building material 2					0.00
building material 3					0.00
building material 4					0.00
building material 5					0.00
building material 6					0.00
building material 7					0.00
building material 8					0.00
building material 9					0.00
building material 10					0.00
surface resistance on internal face	INSIDE				0.04
if wall has a cavity*, enter surface resistance here				cavity 1	
				cavity 2	
U value through building element	in W/m^2K				0.71

U Value through Framed Element	0.27	W/m^2K	
U Value through Cavity Element	0.71	W/m^2K	
width of Frame Element	0.68	m	
width of Cavity Element	0.05	m	
frame spacing	0.73	m	
Table 2a and 2b Combined U Value	**0.30**	W/m^2K	**U-Value of Framed Wall Construction**

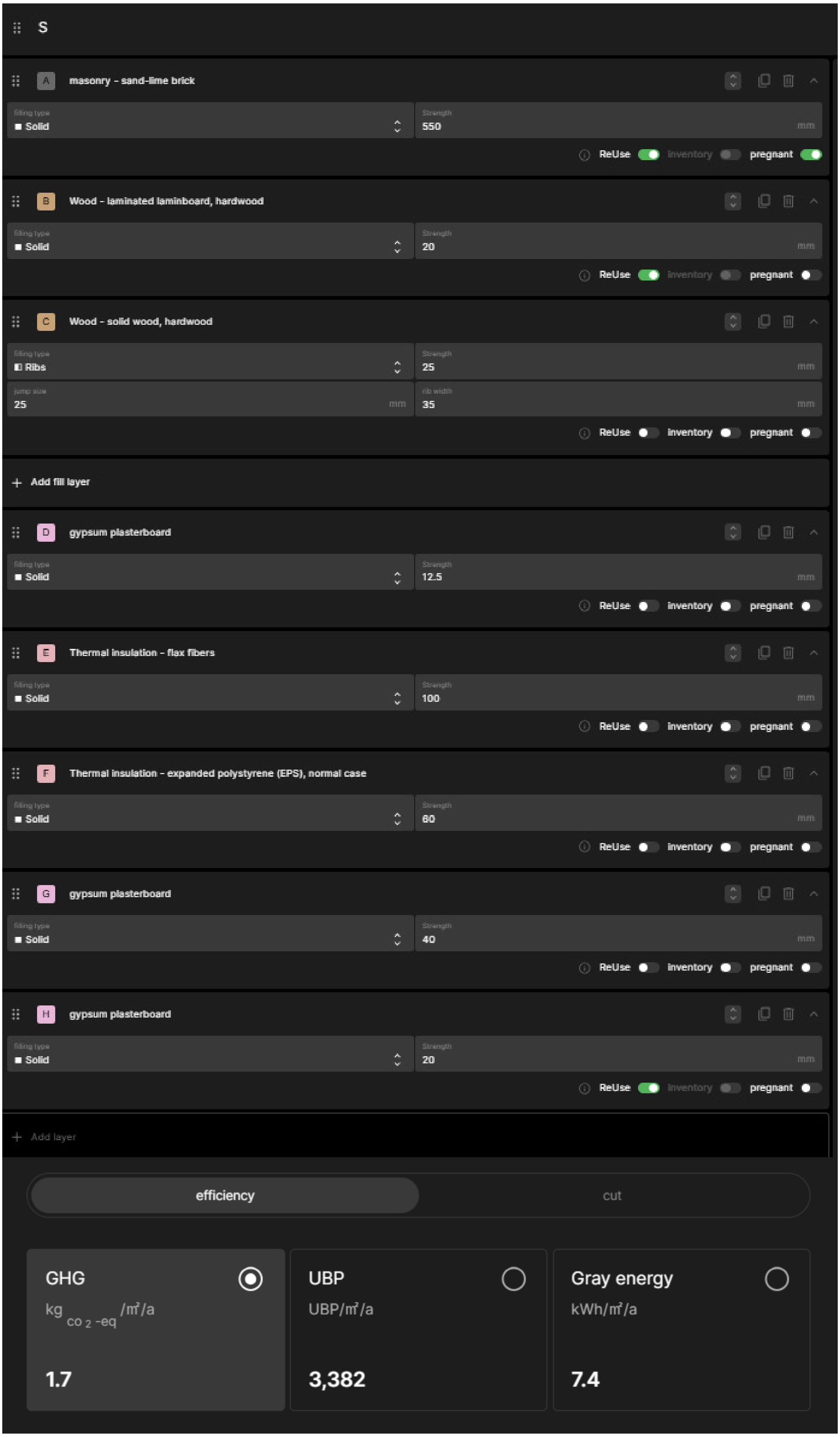
U-value calculations for the Jenners Building

TABLE 1	Non-framed Wall Construction				
		Conductivity	**Resistivity**	**Thickness**	**Resistance**
List materials from inside to outside	Name of building material	K Value of material (W/mK)	r Value of material (mK/W)	material layer (m)	R value of element (m^2K/W)
surface resistance on external face	OUTSIDE				0.12
building material 1	Stone Brick- rubble and ashlar	1.700	0.588	0.550	**0.32**
building material 2	Cellulose Fiber Insulation	0.038	26.316	0.040	**1.05**
building material 3	Lime plaster on a framework of wooden laths	0.600	1.667	0.025	**0.04**
building material 4					**0.00**
building material 5					**0.00**
building material 6					**0.00**
building material 7					**0.00**
building material 8					**0.00**
building material 9					**0.00**
building material 10					**0.00**
surface resistance on internal face	INSIDDE				0.06
if wall has a cavity*, enter surface resistance here				cavity 1	
				cavity 2	
U value through building element	**in W/m²K**				**0.63**

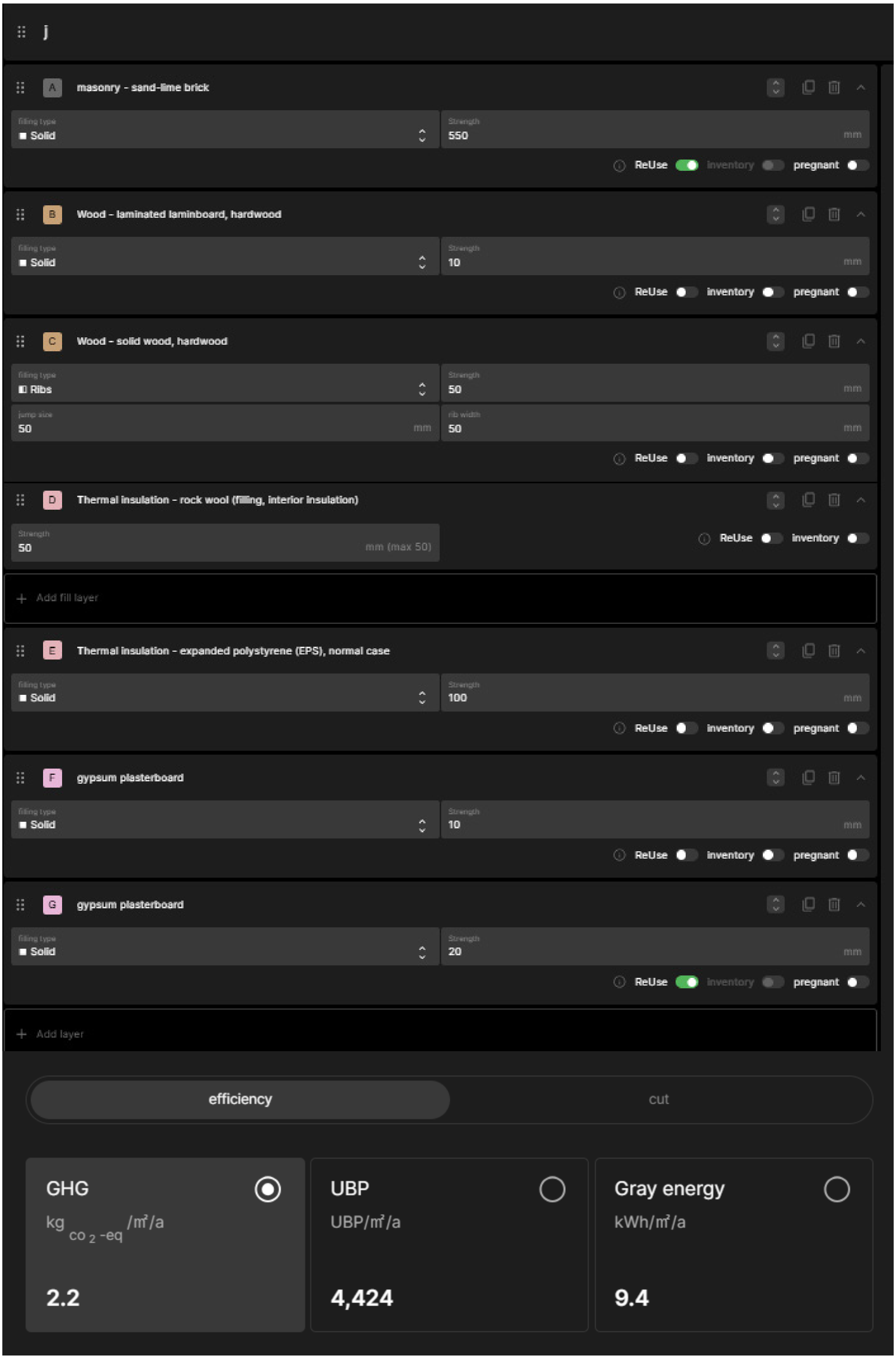
U-value calculations for the Holyrood Park Lodge



Use of Ecotoo for calculating sustainability indicators - Holyrood Park Lodge



Use of Ecotoo for calculating sustainability indicators - South Bridge Resource and Education Centre



Use of Ecotoo for calculating sustainability indicators - the Jenners Building