The case for retrofit; A literature review

Lucas Wolman

Supervised by Dr Jennifer Schooling

University of Cambridge

14/10/2023

Table of Contents

Abstract

Despite growing climate awareness, CO2 emissions from buildings and construction have reached unprecedented levels in our current era. Building energy consumption alone accounts for 17.5% of global greenhouse gas emissions, contributing over 6.5 billion tonnes of CO2e. Traditional approaches have often favoured demolishing and reconstructing buildings to improve performance, yet retrofitting offers a sustainable alternative that deserves more prominent consideration.

Retrofitting is essential in our quest to achieve net-zero targets, as it significantly impacts energy consumption and greenhouse gas emissions. This literature review underscores the importance of prioritising retrofitting for existing buildings within the framework of sustainable development. Retrofit packages encompass a range of improvement activities that enhance existing buildings, offering benefits to all stakeholders. Well-executed retrofits can deliver energy savings, preserve cultural heritage, and reduce greenhouse gas emissions without imposing a heavier financial burden than rebuilding.

The review highlights the critical role of buildings in global energy consumption and greenhouse gas emissions. Government policies, such as minimum energy efficiency standards, underscore the urgency of reducing energy demand and emissions from existing buildings. Despite the potential benefits, historic buildings are often excluded from retrofit initiatives due to the desire to preserve their architectural and historical significance. Funding remains a significant obstacle for retrofitting, with subsidies and incentives aimed at stimulating energy efficiency retrofits. Beyond financial considerations, retrofitting carries social value, generating employment opportunities and improving residents' health and well-being. Additionally, it offers environmental benefits by preventing construction and demolition debris and embodied carbon emissions from construction materials.

The review explores contemporary literature and emerging research areas to address the preference for rebuilding over retrofitting, shedding light on the need for a comprehensive approach that considers environmental, social, and technical factors. The current situation underscores the significance of retrofitting in reducing greenhouse gas emissions and improving energy efficiency. However, local authorities face challenges in understanding their housing stock's performance and require more flexible financing schemes to drive comprehensive retrofit programs. The review also emphasises the importance of accreditation and certification standards, such as BREEAM and LEED, in guiding sustainable retrofit practices.

In conclusion, this literature review highlights the urgent need for further research to identify success factors in retrofitting implementation. A holistic, step-by-step approach to retrofitting, supported by consistent government policies, is crucial to achieving sustainable building practices and mitigating climate change. Local authorities are pivotal in driving successful retrofit programs, leveraging their regional knowledge and expertise. Retrofitting is a compelling alternative to rebuilding, offering a pathway to a more sustainable built environment.

Introduction

We live in an era where CO2 emissions from buildings and construction hit record highs despite the growth in climate awareness. Building energy consumption creates over 6.5 billion tonnes of CO2e, making up 17.5% of greenhouse gas (GHG) emissions globally [1]. While prevalent thinking has led to the demolition and reconstruction of our buildings to improve performance while meeting specific desired stakeholder values, retrofit is an alternative that can reclaim a place within mainstream thinking.

Retrofit is essential in achieving net-zero targets. With its influence on energy consumption and GHG emission, the retrofit of existing buildings should be given due attention concerning sustainable development. Retrofit packages encompass a range of improvement activities to enhance existing buildings and return them to regular use. Well-done retrofits can deliver enhancements for all building stakeholders, save energy, preserve heritage, and reduce greenhouse gas emissions with no heavier financial burden than rebuilding and similar environmental and social parameters.

Buildings are responsible for much of the world's energy use and GHG emissions. In the United Kingdom (UK), buildings consume approximately 40% [2] of total energy, while in the United States (US), this ratio is approximately 50% [3]. Of the total energy use of buildings, 80-90% [4] of life-cycle energy demand is derived from the operational phase. This highlights our existing buildings' significant position in current energy use statistics and how necessary reductions are to achieve net-zero targets. Governmental policy changes emphasise energy reductions, for example, the UK's "Minimum Level of Energy Efficiency" standard from 2018, which sets a minimum energy efficiency level for domestic private rented properties. The standard is enforced by legally requiring all domestic private rented properties to have an Energy Performance Certificate (EPC) of at least E, with proposals raising this limitation to an EPC rating of C by 2028[1].

Retrofits provide opportunities to preserve and protect existing buildings, maintaining their cultural heritage while innovating to improve energy efficiency. It has been found that 14% of European building stock dates before 1919, with another 12% dated between 1919 and 1945 [5]. This corresponds to 55 million homes housing approximately 120 million people. However, historic buildings are often excluded from retrofit initiatives due to the desire to maintain the architectural and/or historical interest that they show, preventing the necessary work needed to be undertaken to reduce operational energy and meet modern criteria. These protections are enshrined in law, such as the UK's Planning (Listed Buildings and Conservation Areas) Act 1990, which provides legal protection for our historic structures at the expense of preventing any such work occurring on these structures. Exceptions to the protections are only assessed on a project-by-project basis, with the listed building consent for Trinity College, Cambridge's retrofit on grade 1 listed "New Court" only being granted after a three-year analysis period ending in presenting the findings to local authorities [6].

[1] On 20 September 2023, the UK Government announced that the proposed energy efficient targets for households raising the minimum EPC rating to be raised from E to C would be scrapped.

Major motivating factors for retrofit are mainly related to financial profitability, including a long-term reduction in energy costs, the reduction of operating expenses, and short amortisation periods [7] [8]. However, funding concerns are cited by 74% of housing associations [9] as a pivotal obstruction to retrofit, both in scale and pace of intervention. Subsidies are available in some territories, with the Kreditanstalt für Wiederaufbau (KfW), a public German banking group, providing three different routes to funding based on appropriate criteria. Grants, tax exemptions, or reductions that directly and indirectly reduce the retrofit costs also exist across European countries to stimulate energy efficiency retrofits in residential and non-residential buildings. Energy savings are comparatively small for heating system retrofits, but retrofit cost-benefit ratios are better than building envelope adjustments. Overall, retrofits have been found to decrease operational costs to between 15% and 62% of the initial value [10].

Social value proves challenging to quantify and struggles to account for the views of the end user/occupier. Beyond the more common measure of cost-benefit ratios, the impact retrofit can have has been demonstrated in domestic and non-domestic settings. Building energy improvements can create jobs, totalling an estimated 141,000 in the New York City (NYC) region by 2030 [11]. In a domestic environment, the health of residents is being jeopardised as homes are not kept dry and warm. The direct medical cost savings from retrofitting these dwellings would be around €9 billion per year if the remedial works were undertaken from the time of publishing (2016) [12]. The environmental value of retrofit can be demonstrated over reconstruction by preventing 90% of the construction and demolition (C&D) debris associated with demolition, equating to 170 million tons in the US [13]. The same sustainability standards exist for both retrofit and rebuild, so retrofit can separate itself through the prevention of emitting the embodied carbon “stored” within the construction materials, as well as the C&D debris and its downstream reuse or landfill waste.

With an ever-growing breadth of knowledge surrounding retrofit and the broadening list of exemplary projects within our built environment, this report attempts to find the reasoning for choosing to rebuild over retrofit.

Current Literature

A recent study reviewed 299 papers (abstracts only) published in 87 journals and six edited (and indexed) books. It then mapped contemporary residential retrofitting literature published in the last two decades in English [14]. The mapping analysis revealed seven emerging research areas within the academic residential retrofitting literature: studies about residential retrofit engaging multiple themes (not focused on one specific aspect), the role of individuals in residential retrofitting (residents, users, homeowners, renters), planning and residential retrofitting policy, projections, simulations and models, the 'life cycle analysis', thermal comfort issues concerning residential retrofitting, and heating-cooling-ventilation systems in residential retrofits.

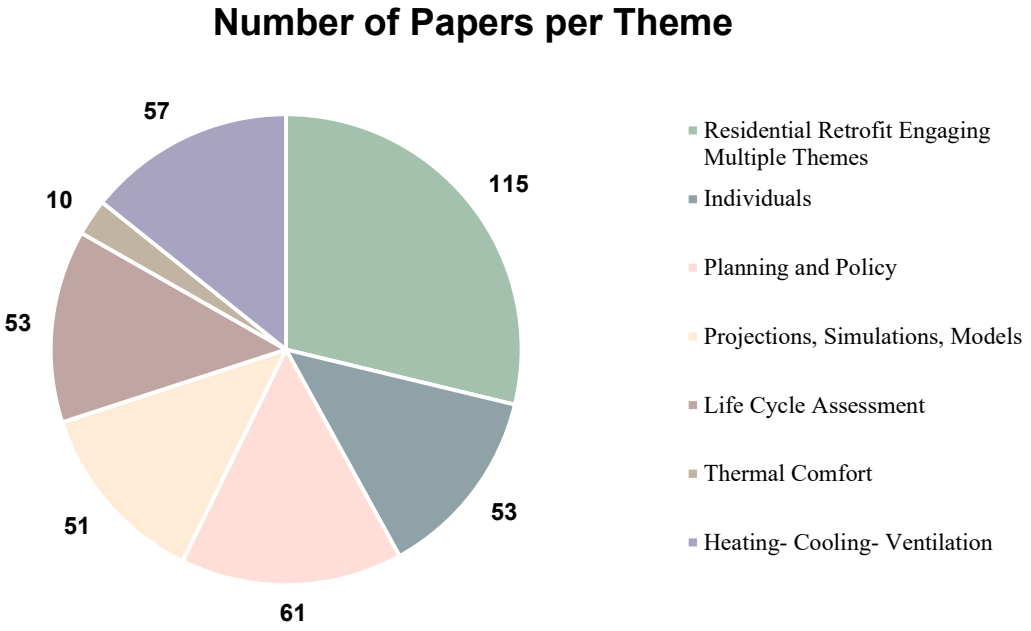

Figure 1 - Number of papers per theme, reproduced from ref. [14]

The literature about residential retrofit is geographically diverse. It includes studies from various countries, with the Global North receiving more representation than the Global South. Many papers identify the UK in their abstracts, with many papers studying the UK residential retrofit practice as a single case study or a comparative one. It should also be acknowledged that the UK has the oldest housing stock in Europe [12], which is also poorly insulated. Therefore, the country faces a more significant challenge and needs extensive retrofitting programmes. Studies that measure the effectiveness or efficiency of retrofitting practices and policies are highlighted in the literature. New technologies are being developed and identified within the literature. A key area of interest is the use of heat pumps. Despite this, thermal comfort is underrepresented within the current literature scope. Thermal comfort is a crucial social and individual aspect of residential retrofitting. The limited literature volume should not be interpreted as a shortfall but as an indication of relatively low engagement. [*ibid*]

Retrofit Policy

A further inspection of the energy retrofit policies for existing buildings in the UK identifies that 27 million UK homes need deep retrofitting to meet the government carbon reduction target by 2050 [15]. Options for both step-by-step and whole-house renovation are required to bring more flexible financing schemes to a long-term strategic plan. The existing strong focus on energy savings and carbon reduction could result in overlooking the indoor health aspects and social sustainability value. Higher humidity problems and overheating risks have occurred in retrofitted buildings [16]. This risk is assigned to enhancing the envelope airtightness and thermal insulation with little attention paid to ventilating the envelope. This literature review further goes on to summarise:

- Raising public awareness on the significance of the national scheme to cut carbon emissions, engaging end-users in the process, and building trust between all stakeholders, including supply chains and investors.
- There is a need for a holistic retrofitting strategy that considers abandoning fossil fuels, reducing heating demand, and equally investing in sustainable construction materials and technologies.
- Embodied carbon in materials and systems should be a key indicator for building retrofit delivery.
- Investing in research and innovative technologies and developing and publicising mass-resource data on retrofitting strategies and schemes at a national scale is vital.

Green Retrofit Design

From a review of the model-based design process from enrolment to evaluation stages, which represents the green retrofitting process in selected publications [17]. Publications show that environmental, social, and technical issues are often examined separately in the decision process of green retrofit design. Publications with questionnaire design are devoted to using life-cycle assessment on existing buildings, but not yet on the stakeholder management and design process and related issues. Few papers have focussed on the systematic factors of retrofitting decisions for academic studies. Different needs and requirements of various stakeholders, including high efficiency, low emission, minimum life-cycle cost, comfort, and safety, are considered mostly for green retrofitting.

The workflow for the design is organised in three stages to incorporate the work in green retrofit design (GRD). The first stage involves decision-making to demolish/enrol in the retrofit behaviour. The second stage requires urgency/availability/technical decision in retrofit. The third stage involves investigating retrofit activities from familiarity through a feasibility study and a series of assessments to seek suppliers and approval from the management team.

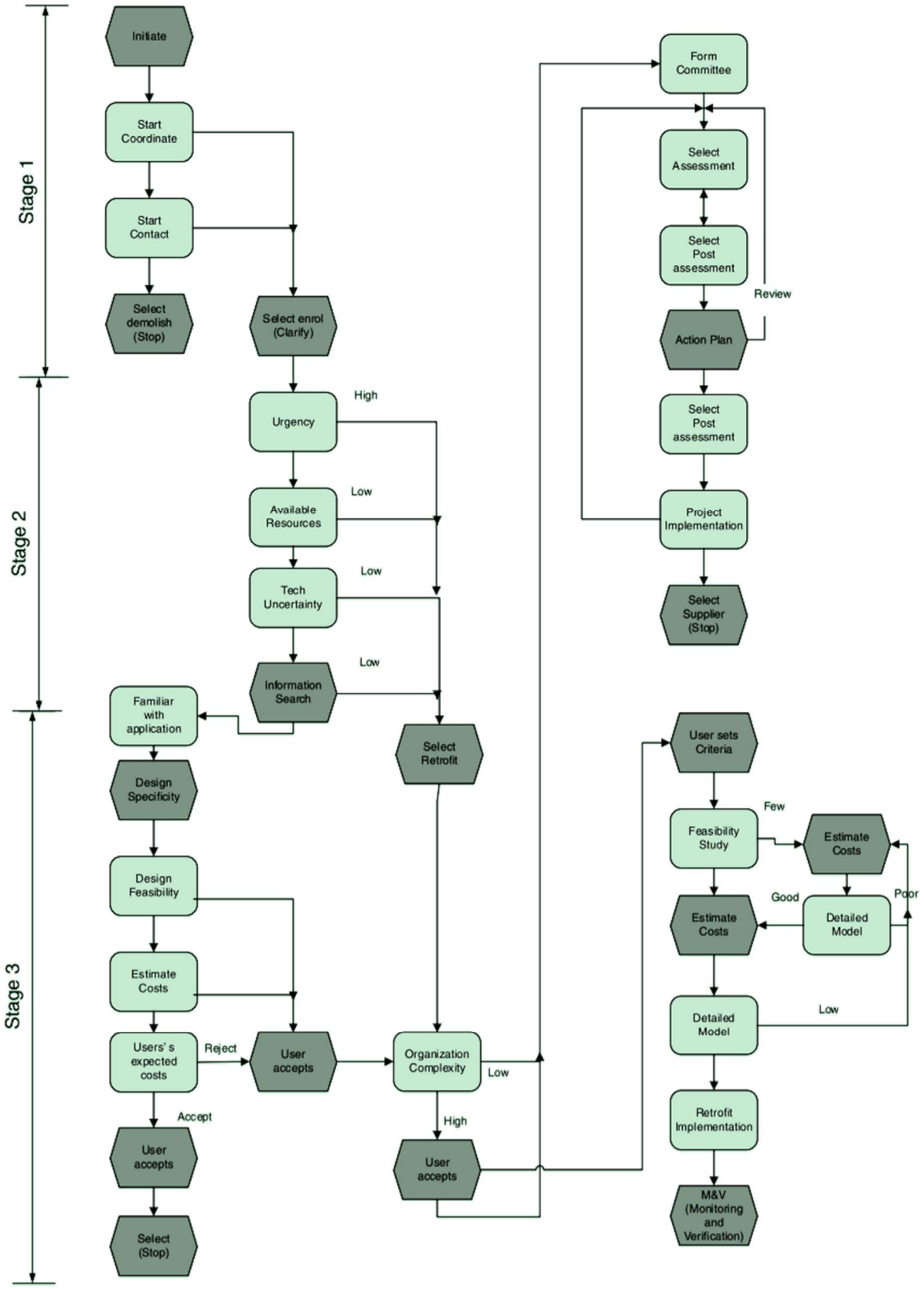

Figure 2 - Proposed framework of GRD with workflow in three stages, reproduced from ref. [17]

Decarbonisation Considerations

When considering between refurbishing and retrofitting or demolition and reconstruction of the building stock, we can aim to address questions like residential building carbon emissions, potential reductions, and associated costs. Typically, this approach uses data on housing age, condition, location, and tenure type, followed by individual building assessments for environmental performance. Estimates of building lifetimes derived from the whole building stock approach have sparked disagreement regarding their usefulness in societal and planning decisions about refurbishment or demolition. The arguments surround the topics of heritage value, embodied investments, urban systems and interdependence, urban design, and decarbonisation of the energy supply [18].

Considering the challenges of insulating a range of dwellings, it becomes evident that those possessing the highest heritage value will likely present the most significant difficulty. Consequently, such historically significant structures are less likely to face demolition. Furthermore, when contemplating demolition and rebuilding, one must consider the substantial energy and carbon investments embedded in the existing infrastructure. This consideration becomes particularly pertinent in the case of greenfield sites, where the environmental costs are notably high. In the context of urban systems and their intricate interdependencies, it is worth noting that older housing, especially those predating the First World War, is often compact and has evolved alongside public transport systems and other urban components. Many of these systems remain operational, emphasising the enduring synergy between the old and the established. The implications of urban design also come into play, as costs are associated with the potential loss of intimacy and the human scale that characterises most of the remaining pre-First World War housing. These factors contribute to these neighbourhoods' unique charm and character, making preservation a compelling consideration. Finally, when exploring the path towards decarbonising energy supply, modelling various scenarios reveals that plausible improvements to buildings and energy supply and conversion systems may not significantly reduce CO2 emissions by 2050. Thus, the rate of demolition does not appear to be a decisive factor in achieving substantial emissions reductions, underlining the importance of addressing other aspects of sustainability in the built environment.

Present Situation

The operational energy of residential buildings contributes 23% of the UK's greenhouse gas emissions. Retrofitting to reduce energy consumption can also deliver other benefits, including reduced fuel bills and increased thermal comfort. These benefits can be achieved through improving energy performance through improvements to the building fabric, installing more efficient appliances and controls, and improving occupant understanding of how energy is used in the home. Progress can also be made through switching fuel sources, such as using renewable resources on-site to generate heat or power or connecting to neighbourhood energy supplies such as low-carbon heat networks [19].

Local Authorities

The capacity of different local authorities (LA) varies significantly, encompassing differences in their knowledge, skills, and data access [20]. However, severe resource shortages are a common challenge. There is an acknowledgement that retrofitting plays a pivotal role in achieving these objectives. At present, LA initiatives primarily concentrate on available funding resources. Therefore, there is an eagerness within LAs to serve as catalysts by using their influence and ongoing programs to maximise public funding and social housing budgets. There is also an exploration into options for LAs to act as intermediaries or financiers, all while acknowledging varying risk tolerance levels among stakeholders. Government policy tends to be fragmented and sporadic, often lacking the acknowledgement to implement programs across various communities effectively; comprehensive support is essential for all housing tenures. This support is necessary to facilitate cost-effective improvements for entire streets or neighbourhoods. Local authorities possess the required in-depth knowledge of their regions, encompassing housing inventory and the resident communities. Consequently, they are in an ideal position to conceptualise and oversee comprehensive programs that span various housing tenures.

Two distinct bottom-up building stock modelling approaches, archetype-based and building-by-building, inform building policies [21]. Archetype-based methods, with their reduced data requirements and lower computational costs, dominate modelling energy consumption, conducting life-cycle assessments, and evaluating indoor environmental quality. Conversely, building-by-building approaches excel at capturing individual building characteristics, thanks to advances in data acquisition and computational techniques. Both models have inherent uncertainties impacting reliability, but integrating stochastic archetype models and digital twin models shows promise in addressing this. Additionally, the system dynamics modelling approach adeptly handles policy complexities and conflicts, enabling the achievement of multiple policy objectives.

Private Landlords

Upon a survey of private landlords across the UK, the following recommendations help the private sector better decarbonise their assets [22].

To optimise energy efficiency standards in the property sector, policymakers should abandon a uniform approach and instead tailor energy efficiency proposals to accommodate properties' diverse ages, conditions, and sizes. This approach would enable targeted grants and funding support based on the specific archetype of a property rather than solely considering its tenure, ultimately promoting maximum energy efficiency across the board. Such a strategy ensures that properties remain in the private rented sector and prevents buildings from becoming prohibitively expensive to upgrade. Furthermore, for effective planning and execution of home retrofitting, homeowners and landlords require clear guidelines on the necessary energy efficiency levels, associated costs, and implementation timelines. No definitive legislative targets exist, leaving only recommendations from various reports. To rectify this, the UK and

Devolved Governments must establish a comprehensive, long-term policy framework and legislate specific targets for Energy Performance Certificate (EPC) ratings, facilitating the practical implementation of energy efficiency measures.

In tandem with these measures, a national communications campaign aimed at tenants, landlords, and homeowners is essential to meet decarbonisation objectives. Convincing these stakeholders of the benefits of retrofitting and energy efficiency improvements is pivotal. The cooperation and perspective of landlords and owner-occupiers significantly influence the success of retrofitting initiatives, directly impacting the adoption of energy efficiency enhancements and retrofit programs, even when government funding is available.

Furthermore, the exploration of a Property Passport could stimulate the uptake of energy efficiency improvements. This transferable information tool would facilitate essential data exchange among building owners and support maintaining a long-term decarbonisation vision for the property. Not intended to replace Energy Performance Certificates (EPCs), the Property Passport would complement them by digitising EPC data and supplementing it with additional information over time. The passport would offer detailed guidance on actions required and already undertaken to enhance property efficiency, utilising building fabric and operational data to assist building owners and occupants in making informed decisions for improved energy efficiency in buildings.

There is compelling evidence to suggest that implementing tax incentives can enhance the appeal of investments, thereby encouraging retrofit initiatives. The survey indicated that 68% of agents advocate for an extension of support mechanisms. They contend that allowing energy efficiency enhancements to be offset against capital gains tax could significantly bolster the attractiveness of such investments. A relatively straightforward tax restructuring, allowing deductions for energy performance improvements against rental income, has the potential to further entice landlords towards sustainable investment practices. Individual landlords currently face an income tax liability on their rental properties, akin to taxation on other forms of earned income. Other alternative incentives are vouchers to cover the costs of retrofit evaluations or loans and grants to pay for energy efficiency improvements. *[ibid]*

Accreditation and Certification

With the growing demand for sustainable buildings, there has been a proliferation of accreditations and certifications, with their definitions and constraints lending themselves to a distracted approach to sustainability. These standards could be regarded as the initial step in a more extensive discourse and initiative towards sustainability. A collaborative effort between building stakeholders is required to integrate comprehensive design measures that simultaneously diminish environmental impact and fulfil building users' requirements. Two pre-eminent standards (BREEAM and LEED) focus on the in-use operation of a building rather than the carbon emissions and resource impact of how it is being designed and constructed. To achieve BREEAM's highest rating, a building needs 85 credits; however, only six credits are available for approaches that tackle embodied carbon [23]. Understanding a building's

environmental impact is crucially facilitated by considering whole-life carbon, providing a comprehensive means to guide design choices.

There is a perceived risk [24] that within these schemes, which currently place a low value and emphasis on the circular economy, innovative concepts such as designing for circularity, implementing product take-back initiatives, favouring material leasing over ownership, promoting refurbishment and remanufacturing, and advancing reverse logistics (the act of improving the recovery of used materials) may go unnoticed.

One recent pioneering retrofit project of the Entopia Building, home of the Cambridge Institute for Sustainability Leadership (CISL), took an alternative view of these well-established standards. It was acknowledged by CISL in consultation with the design stage team that no singular system possessed adequate comprehensiveness in its objectives or targets, so the decision was made to pursue multiple certifications. Alongside targetting BREEAM Outstanding, WELL Gold, and EnerPHit Classic certifications—which combine to create a robust and expansive sustainability framework for construction projects—principles which are not well defined by any standards, became their in-house targets, these being circular economy principles, use of bio-based materials, and whole life-cycle embodied carbon performance. In summary, the following targets were included in the final brief [25]:

- BREEAM Outstanding
- EnerPHit Classic
- WELL Gold
- Low embodied carbon (target < 300kg $CO2/m^2$ for 100-year life)
- Targeting 70% bio-based materials by mass, with responsible sourcing and traceability
- Use of recycled and reclaimed materials, emphasising Circular Economy principles

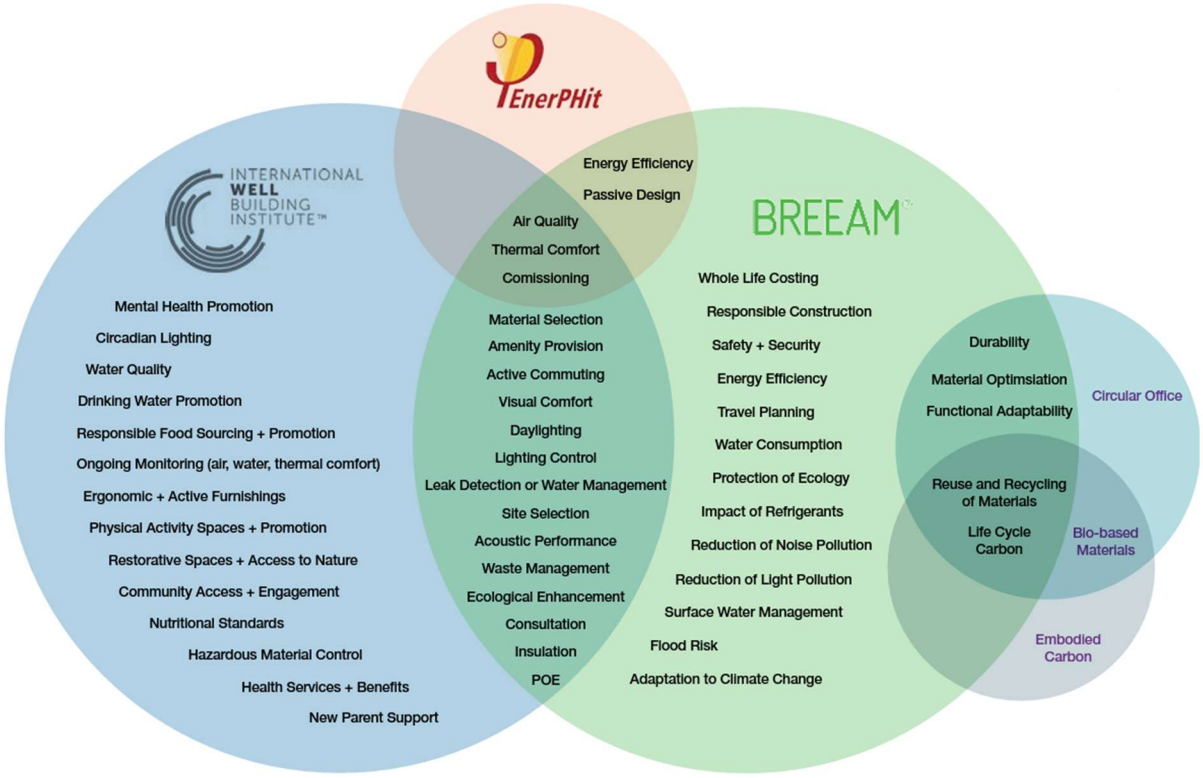

Figure 3 - Key project standards for the Entopia Building, reproduced from ref. [25]

A universal solution is not suitable for every situation; instead, various policies and standards can be employed based on the unique characteristics of each retrofitting case. However, there is an immediate requirement for a systematic, step-by-step approach to retrofitting.

Retrofit Barriers

Local authorities encounter a hurdle in understanding their housing stock's performance, which is vital for making informed investment choices and determining priority areas or estates [26]. Within the London borough of Newham, the estimated reduction in CO2 emissions for every pound spent on transitioning to LED light bulbs stands at 1.468 kilograms. The data further includes calculations for expenses associated with insulation installation, electric heat pump adoption, and solar panel integration, alongside their expected carbon savings. Projections indicate that the initial capital outlay for a comprehensive retrofit of an average London property could range from £26,816 to £36,595. When extrapolated for the entire city, these retrofit costs collectively exceed £100 billion.

Addressing the challenge of crafting enticing home funding options while simultaneously ensuring profitability for lenders and investors is a complex endeavour. Striking this balance necessitates careful consideration and innovation within the financial landscape [20]. Furthermore, the constrained size of the market and individual projects can act as obstacles to the evolution of novel financial products. The limited scope and scale often impede the development of creative solutions catering to diverse homeowner needs.

Moreover, a perceived technology risk exists associated with products and services lacking a substantial track record. This apprehension can deter potential investors and stakeholders, highlighting the importance of establishing credibility and reliability in emerging technologies. Adding to the complexity are Sections 56 and 75 of the Consumer Credit Act [27], which places the responsibility on finance providers in cases where contracts remain unfulfilled. This legal framework adds another layer of consideration for financial institutions and underscores the need for rigorous risk assessment and management. Lastly, a notable hindrance lies in the absence of consistent, long-term government policy. The absence of a clear and enduring regulatory framework can disrupt financial planning and decision-making, complicating efforts to provide stable and sustainable funding solutions in the housing market.

Conclusion

Despite substantial efforts in this field, this literature review uncovers a critical gap in our understanding of retrofitting. Specifically, there is a lack of research dedicated to identifying the pivotal factors that contribute to the successful execution of retrofitting in existing buildings. Studies have shed light on numerous obstacles and challenges that deter building stakeholders from embracing green retrofitting solutions. Consequently, given the constraints of prior research and insights from contemporary studies, there is an urgent need to redirect future research endeavours towards exploring the factors that underpin successful retrofitting implementation. This focus on success factors is crucial for enhancing ongoing retrofitting initiatives to combat climate change and curb greenhouse gas emissions. Moreover, identifying these success factors should be firmly grounded in a comprehensive understanding of stakeholders' challenges.

A step-by-step, whole-house renovation approach is imperative to advance this agenda, accompanied by introducing more flexible financing schemes integrated into a long-term strategic plan. Raising public awareness about the national scheme to reduce carbon emissions is vital, involving end-users in decision-making and fostering trust among all stakeholders, including supply chains and investors. A holistic retrofitting strategy is essential, encompassing the abandonment of fossil fuels, a reduction in heating demand, and equitable investments in sustainable construction materials and technologies.

Measuring embodied carbon in materials and systems must be a pivotal indicator for building retrofit delivery. It can either be integrated into a comprehensive certification framework or stand alone as a vital metric in its own right. Investing in research and innovative technologies, as well as developing and disseminating extensive resource data on retrofitting strategies and schemes at a national scale, is of paramount importance.

Additionally, the establishment of consistent, long-term government policies is imperative. Comprehensive support is indispensable for all housing tenures to facilitate cost-effective street or neighbourhood-level improvements. Local authorities possess the requisite in-depth knowledge of their regions, including housing inventory and resident communities, making their involvement instrumental in achieving successful retrofitting outcomes.

References

[1] H. Ritchie and M. Roser, “Emissions by sector,” 2020. [Online]. Available: https://ourworldindata.org/emissions-by-sector. [Accessed 28 July 2023].

[2] K. Harris, “Digest of UK Energy Statistics (DUKES): energy,” Department for Energy Security and Net Zero, London, 2023.

[3] United States Energy Information Administration, “Annual Energy Review 2010,” United States Department of Energy, Washington, DC, 2011.

[4] T. Ramesh, R. Prakash and K. Shukla, “Life cycle energy analysis of buildings: An overview,” *Energy and Buildings,* vol. XLII, no. 10, pp. 1592-1600, 2010.

[5] A. Troi, “Historic buildings and city centres – the potential impact of conservation compatible energy refurbishment on climate protection and living conditions,” Institute for Renewable Energy, Bolzano, 2011.

[6] Architecture Today, “New Court at Trinity College Cambridge,” 2023. [Online]. Available: https://architecturetoday.co.uk/new-court-trinity-college-cambridge-5th-studio-max-fordham/. [Accessed 15 August 2023].

[7] I. Stieß and V. Van der Land, “Just another business case?: Enhancing the agency for energy-efficient refurbishment among private homeowners,” Delft University of Technology, Delft, 2010.

[8] M. Gossen and C. Nischan, “Regionale Differenzen in der Wahrnehmung energetischer Sanierungen,” Institut für ökologische Wirtschaftsforschung, Berlin, 2014.

[9] National Housing Federation, “New NHF research highlights barriers to retrofitting homes,” 2020. [Online]. Available: https://www.housing.org.uk/resources/barriers-retrofitting-homes/. [Accessed 15 August 2023].

[10] Z. Mayer, R. Volk and F. Schultmann, “Analysis of financial benefits for energy retrofits of owner-occupied single-family houses in Germany,” *Building and Environment,* vol. CCXI, 1 March 2022.

[11] Urban Green, “Retrofit Market Analysis,” 18 June 2019. [Online]. Available: https://www.urbangreencouncil.org/20b-building-energy-retrofit-market/. [Accessed 17 August 2023].

[12] S. Nicol, M. Roys, D. Ormandy and V. Ezratty, “The cost of poor housing in the European Union,” BRE Trust, Watford, 2016.

[13] United States Environmental Protection Agency , “Advancing Sustainable Materials Management: 2018 Fact Sheet,” United States Environmental Protection Agency, Washington DC, 2020.

[14] B. Serin, “Reviewing Residential Retrofitting Literature,” UK Collaborative Centre for Housing Evidence, Glasgow, 2023.

[15] AECB, “Advanced level retrofit e-learning programme,” Llandsul, 2021.

[16] M. Ortiz, L. Itard and P. M. Bluyssen, “Indoor environmental quality related risk factors with energy-efficient retrofitting of housing: A literature review,” *Energy and Buildings,* vol. CCXXI, no. 1, 2020.

[17] S. Bu, G. Shen, C. J. Anumba, A. K. Wong and X. Liang, “Literature review of green retrofit design for commercial buildings with BIM implication,” *Smart and Sustainable Built Environment,* vol. IV, no. 2, pp. 188-214, 2015.

[18] R. Lowe, “Technical options and strategies for decarbonising UK housing,” *Building Research & Information,* vol. XXXV, no. 4, pp. 412-425, 2007.

[19] K. Crawford, C. Johnson, F. Davies, S. Joo and S. Bell, “Demolition or Refurbishment of Social Housing? A review of the evidence,” UCL, London, 2014.

[20] A. Boyle, “Retrofit Funding Propositions,” UK Green Building Council, London, 2021.

[21] J. Dong, Y. Schwartz, A. Mavrogianni, I. Korolija and D. Mumovic, “A review of approaches and applications in building stock energy and indoor environment modelling,” *Building Services Engineering Research & Technology,* vol. 0, no. 0, pp. 1-22, 2023.

[22] Propertymark, “Energy efficiency in UK property: Where to go from here?,” 17 August 2023. [Online]. Available: https://www.propertymark.co.uk/resource/energy-efficiency-in-uk-property.html. [Accessed 14 October 2023].

[23] BRE, “BREEAM technical standards,” 2023. [Online]. Available: https://bregroup.com/products/breeam/breeam-technical-standards/. [Accessed 1 September 2023].

[24] N. Forest, “Why we should call time on sustainable accreditations,” 2023. [Online]. Available: https://www.isgltd.com/en/what-we-think/why-we-should-call-time-on-sustainable-accreditations. [Accessed 11 July 2023].

[25] J. Blaylock, P. Courtice, T. Forman, J. French, J. Reynolds and J. Cole, “Building Entopia,” Cambridge Institute for Sustainability Leadership, Cambridge, 2022.

[26] SNC Lavalin, “Atkins launches Digital Dashboard to reveal costs of meeting EPC 2030 deadline,” 2023. [Online]. Available: https://www.engineeringnetzero.com/retrofit-dashboard-helps-visualise-pathway-to-net-zero-for-residential-buildings/. [Accessed 5 July 2023].

[27] Parliament of the United Kingdom, “Consumer Credit Act 1974,” 31 July 1974. [Online]. Available: https://www.legislation.gov.uk/ukpga/1974/39/contents. [Accessed 6 September 2023].

[28] J. Alabid, A. Bennadji and M. Seddiki, “A review on the energy retrofit policies and improvements of the UK existing buildings, challenges and benefits,” *Renewable and Sustainable Energy Reviews,* vol. CLIX, no. 1, 2022.

[29] The Scottish Government, “Scottish household survey 2019: annual report,” The Scottish Government, Edinburgh, 2020.