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Article

Integrating Circular Economy Principles into Energy-Efficient Retrofitting of Post-1950 UK Housing Stock: A Pathway to Sustainable Decarbonisation

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Abstract: The United Kingdom's legislated commitment to net-zero carbon emissions by 2050 necessitates urgent decarbonisation across all economic sectors. The residential housing sector presents a particularly significant opportunity, accounting for approximately 20% of national greenhouse gas emissions. A substantial portion of the UK housing stock comprises post-1950 dwellings constructed during periods of rapid expansion, when resource efficiency and thermal performance were subordinated to addressing immediate housing shortages. These buildings emerged in an era characterised by perceived energy abundance and limited awareness of environmental consequences, resulting in unanticipated energy performance deficiencies that now challenge contemporary climate objectives. While energy-efficient retrofitting has become integral to national decarbonisation policy, current initiatives predominantly emphasise technological interventions—such as thermal insulation, fenestration improvements, and heating system upgrades—often without adequately addressing broader sustainability imperatives or natural resource stewardship. This research proposes a paradigmatic reorientation through the systematic integration of Circular Economy (CE) principles into residential retrofit practices. CE approaches—characterised by material circularity, waste minimisation, adaptive design strategies, and comprehensive lifecycle assessment—offer enhanced environmental sustainability and economic resilience compared to conventional retrofit methodologies. The investigation employs a multi-methodological approach encompassing systematic literature analysis, comprehensive policy review, stakeholder engagement, and critical evaluation of retrofit implementation across diverse UK contexts. This research identifies significant barriers to CE integration, including regulatory constraints, workforce capability gaps, and supply chain fragmentation, while also recognising potential enablers for transition. Building upon this analysis, the study develops an evidence-based decision-making framework that systematically aligns retrofit interventions with CE principles. This integrative framework is designed to inform policymakers, industry practitioners, and researchers in conceptualising and implementing retrofit strategies that simultaneously enhance energy performance, optimise material circularity, minimise embodied carbon, and strengthen long-term environmental and economic resilience. The findings advance a holistic, systems-oriented approach to residential retrofitting that positions the housing sector as a critical catalyst in the UK's transition toward a circular, low-carbon built environment.

Keywords: circular economy; energy-efficient retrofit; post-1950 housing; sustainable construction; UK housing stock; decarbonisation; embodied carbon; lifecycle thinking; residential buildings; built environment

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1. Introduction

The United Kingdom's residential sector is a significant contributor to national carbon emissions, accounting for approximately 20% of the total, primarily due to the prevalence of poorly insulated and outdated housing stock constructed during the post-war period [1]. These buildings often lack modern energy-efficient characteristics, explaining associated excessive energy consumption

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and associated greenhouse gas emissions [2]. Retrofitting these structures to energy-efficient standards is imperative to meeting the UK's net-zero targets by 2050 [3].

Traditional retrofitting strategies have predominantly focused on enhancing thermal performance and reducing operational energy use [4]. While these measures are essential, they often overlook the full lifecycle impacts of materials and construction processes, including embodied carbon emissions and resource depletion [5]. The need to adopt the lifecycle approach to retrofitting is overwhelming owing to embedded circular economy (CE) attributes in promoting the reuse of materials, extending building lifespans, and minimising reliance on virgin resources [6]. Integrating CE principles into retrofitting practices not only decouples construction activities and raw material consumption intensity, but it also reduces the ecological footprints of the built environment, aligning environmental objectives with long-term economic benefits. Successfully done, this strategy offers immense potential for enhanced UK's nationally determined contributions (NCDs) to global climate action [7].

This study aims to develop a comprehensive decision-making framework that integrates CE principles into energy-efficient retrofitting of post-1950 UK housing. By synthesising current literature, policy analyses, stakeholder insights, and technical assessments, the framework seeks to guide stakeholders in the implementation of sustainable and circular retrofitting.

2.1. Energy-Efficient Retrofitting in the UK

Recent advancements in energy retrofitting have focused on improving thermal insulation, upgrading heating, ventilation, and air conditioning (HVAC) systems, and installing renewable technologies such as solar panels [8]. However, the uptake of energy retrofitting measures remains low due to high upfront costs, knowledge gaps among stakeholders, and fragmented supply chains [9]. Government initiatives like the Green Homes Grant and the Energy Company Obligation (ECO4) have attempted to address these barriers but have faced implementation challenges, including administrative complexities and limited engagement from contractors [10].

Moreover, energy retrofits often result in unintended consequences, such as reduced indoor air quality or the use of materials with high embodied carbon [11]. A narrow focus on operational energy savings can miss opportunities for holistic sustainability improvements, highlighting the need for integrated approaches that consider the full lifecycle impacts of retrofitting interventions [12].

2.2. Circular Economy in the Built Environment

The concept of the circular economy has gained traction in the construction sector by promoting practices such as material reuse, design for disassembly, and waste minimisation [13]. In the context of housing retrofits, CE principles can complement energy efficiency measures by ensuring that materials used have lower embodied carbon and are part of a sustainable resource loop [2]. Strategies like adaptive reuse, closed-loop recycling, and the use of bio-based building materials can reduce the environmental footprint of retrofitting projects [6–8].

Despite the potential benefits, integrating CE principles into retrofitting remains underexplored, especially concerning existing UK housing [14]. There is a lack of comprehensive frameworks that guide stakeholders in incorporating CE strategies into retrofit planning and execution, underscoring the need for research that bridges this gap [15].

2.3. Gaps in Existing Research

The integration of circular economy (CE) principles within the retrofitting sector represents a critical yet under-developed approach to addressing the environmental challenges posed by the built environment. While substantial literature exists examining either retrofitting or circular economy in isolation, their intersection remains inadequately explored [16,17]. This study serves to critically examines the significant knowledge gaps that impede the effective implementation of circular economy principles in retrofitting practices, with particular attention to post-1950 UK housing stock.

First, it important that the conceptual and definitional ambiguities associated with the concept of circular economy are understood. The circular economy concept remains plagued by definitional inconsistencies when applied to retrofitting contexts. Indeed, the construction sector has adopted circular terminology without sufficient adaptation to the unique characteristics of building renovation and retrofit [18]. This conceptual ambiguity has resulted in what has been described as "circular economy washing," where superficial CE measures are implemented without systemic change [19].

Particularly, this highlights the absence of standardized frameworks that differentiate between truly circular approaches and incremental improvements in waste management for retrofitting projects [20].

2.4. Technical Implementation Barriers

The technical feasibility of circular retrofitting faces substantial knowledge deficits [21]. Unlike new construction, where design for disassembly can be integrated from inception, retrofitting projects must contend with existing structures not originally conceived with circularity in mind [22,23]. Significant gaps in understanding how to recover materials from existing buildings without diminishing their technical properties and economic value exist [23]. Indeed, there is limited research on connection systems that would enable the non-destructive disassembly of retrofitted components for future reuse [24].

The interface between new and existing materials in circular retrofits presents another critical knowledge gap. The assertion that "the compatibility of recovered materials with modern building systems remains largely unexamined," particularly regarding long-term performance and stability is forcefully argued [25]. This technical uncertainty contributes significantly to stakeholder reluctance to adopt circular approaches in retrofitting projects [26].

2.5. Economic and Market Constraints

The economic viability of circular retrofitting approaches remains insufficiently researched, and the absence of robust cost-benefit analyses that account for the full lifecycle impacts of circular retrofitting strategies is highlighted as a significant gap in knowledge [27]. Conventional economic assessments fail to capture the "externalised benefits" of circular approaches, including reduced resource depletion and waste management costs [28].

The market infrastructure to support circular retrofitting is similarly underdeveloped, and there are significant gaps in understanding how to establish reliable supply chains for secondary materials in retrofitting projects [29]. Evidence abounds that "without established markets for recovered building components, circular retrofitting remains economically unviable for most practitioners" [30]. Despite these challenges, little research has been conducted on alternative business models specifically tailored to circular retrofitting [31].

2.6. Policy and Regulatory Framework Deficiencies

Current building regulations and standards predominantly focus on operational energy efficiency, with limited consideration of material circularity in retrofitting contexts [18]. Similarly, overt policy emphasis on operational carbon reductions without equivalent attention to embodied carbon and material flows hinders retrofitting [16]. This is further complicated by the persistent absence of circularity metrics within building assessment methods and certification systems relevant to retrofitting [28]. Above all, the fragmentation of policy approaches across different governance levels further complicates the implementation of circular retrofitting [32]. This is further compounded by the apparent disconnection between national sustainability targets, local planning policies, and building regulations, constituting huge bottlenecks to holistic circular approaches in retrofitting [17]. Bridging these apparent gaps is a necessary prerequisite to holistic retrofit effective policy instruments necessary for effective sustainable retrofitting.

2.7. Social and Behavioural Dimensions

The social aspects of implementing CE in retrofitting constitute perhaps the most significant knowledge gap. Homeowner perceptions regarding reused materials in retrofit projects remain largely unexplored [29]. Although extensive research on consumer acceptance of energy efficiency measures abounds, similar efforts looking at attitudes toward material circularity in home renovations is virtually non-existent [33]. Additionally, the challenges posed by skills gap among construction professionals regarding circular retrofitting techniques are real [22]. The required competencies for successful implementation of circular approaches in retrofitting differ substantially from conventional renovation methods yet training programs and educational frameworks addressing these differences remain underdeveloped [18].

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2.8. Integration with Energy Efficiency Objectives

A critical knowledge gap exists in understanding potential synergies and conflicts between material circularity and energy efficiency in retrofitting projects. In practice, it has been observed that the optimisation of operational energy performance often occurs at the expense of material circularity [16]. In particular, examining how to balance these potentially competing objectives remains is long overdue [16]. Though such trade-offs are often complex, effective framework to guide practitioners through these complexities cannot be overemphasised [20]

Thus. the significant knowledge gaps identified across conceptual, technical, economic, policy, and social dimensions substantially impede the integration of circular economy principles into retrofitting practices. Addressing these gaps requires interdisciplinary research that bridges theoretical and practical aspects of circular retrofitting, particularly for the challenging context of post-1950 UK housing stock [21]. As the construction sector faces increasing pressure to reduce both operational and embodied environmental impacts, developing robust frameworks for circular retrofitting represents an urgent research priority.

3. Methodology

This research employs a mixed-methods approach to formulate a decision-making framework for circular economy (CE) integration in energy-efficient retrofitting of post-1950 UK housing stock. The methodological design addresses the complex socio-technical challenges inherent in sustainable retrofitting through three interconnected components:

Qualitative Document Analysis

A critical examination of policy frameworks, technical case studies, and scholarly literature was undertaken to map the theoretical and practical landscape of CE-retrofitting integration [34]. This analysis specifically targeted the identification of implementation gaps, policy inconsistencies, and successful intervention models across varied housing typologies. The document selection process followed systematic inclusion criteria as has been recommended to mitigate selection bias and ensure comprehensive coverage of both mainstream and alternative approaches to retrofit strategies [35].

Similarly, in-depth, semi-structured interviews (n=27) were conducted with key actors across the retrofitting value chain, strategically selected to represent diverse perspectives including policy implementation agencies, building professionals, material suppliers, and end-users [36] The interview protocol employed critical incident technique to elicit concrete experiences rather than aspirational statements, thereby generating data grounded in practical realities [37,38]. This approach revealed tensions between theoretical CE principles and on-ground implementation challenges as relates to embodied carbon in buildings [16].

The emergent framework was developed through iterative thematic analysis of both datasets, with particular attention to contradictions and convergences between documented best practices and stakeholder experiences [39]. Draft frameworks underwent two validation cycles with expert panels following the Delphi method to test applicability across diverse housing contexts and identify potential implementation barriers [40]. This iterative validation process helped refine the framework's practical utility while acknowledging its inherent limitations and context-specificity to the built environment [40].

The methodological approach acknowledges potential limitations in stakeholder representation and the evolving nature of CE practices, addressing these through transparent documentation of participant selection holds the key to effective circularity in the construction sector, enhancing sustainable retrofitting.

4. Findings and Discussion

Current retrofitting practices in the UK demonstrate a narrow focus on operational energy savings without adequately considering whole-lifecycle impacts. This findings validates previous findings that contemporary retrofitting methods often neglect embodied energy and carbon considerations [43]. This study reveals two significant limitations in current retrofitting practices, and this include fragmented implementation owing to the siloed nature of the construction industry. As a result, consistency is lacking in the application of sustainable retrofitting practices, thereby constituting institutional barriers to holistic retrofitting approaches [44]. Secondly, inadequate guidelines where

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standardised protocols for integrating Circular Economy (CE) principles into retrofitting projects are missing, hence the absence of regulatory frameworks for embedding circular thinking in building renovation standards [45]. The implication being that materials with high embodied energy and carbon are specified for retrofitting [43].

The study also identified several significant opportunities for integrating CE principles into retrofitting practices, validating and extending findings from previous studies on resource efficiency and material reuse [46]. Survey respondents firmly believe that salvaging and reusing materials such as bricks, timber, and metal components can significantly save on embodied energy and carbon emissions in retrofitting projects. This process not only conserves natural resources but also reduces wastes that would otherwise contribute to landfills" [46].

Similarly, design for disassembly is considered critical to sustainable retrofitting where the implementation of modular design principles and standardised connections emerged as a critical strategy for facilitating future circularity. This finding confirms the assertion that design for disassembly is a major paradigm shift in building lifecycle thinking [41,42]. This means that components can be easily removed, replaced, or upgraded without extensive labour or waste generated by prioritising modular design and using standardised connections. This approach not only streamlines maintenance, enabling quicker repairs or upgrades, but also enhances the sustainability of structures [42]. Indeed, this finding extends previous works that 40% reductions in renovation waste through the implementation of modular systems is possible in residential retrofits [47,48].

Also, the study identified significant potential in incorporating bio-based materials such as hempcrete and cross-laminated timber to enhance thermal performance while reducing environmental impact [48]. This validates research earlier research that bio-based insulation materials in retrofitting projects could achieve comparable thermal performance to conventional materials while sequestering carbon [48]. Thus, the integration of comprehensive lifecycle assessment methodologies emerged as crucial for informed decision-making. This confirms earlier findings that "projects employing lifecycle assessment tools consistently achieved superior environmental outcomes through more informed material selection" [49].

Stakeholder interviews revealed both awareness of CE benefits and significant barriers to implementation. These insights validate and extend previous research in several key areas. For example, a significant finding was that many stakeholders lack sufficient knowledge of CE practices, confirming "critical knowledge deficits among building professionals regarding circular economy principles" [50]. The interviews revealed that this knowledge gap extends across the supply chain, from designers to installers, limiting effective implementation of CE strategies.

The research also identified substantial economic barriers, particularly concerning initial investment costs and uncertain returns. For example, "High upfront costs and uncertain return on investment are significant barriers that discourage both homeowners and developers from embracing circular economy (CE)-based retrofitting strategies" [51]. This finding validates earlier work of a 15-30% premium for circular retrofitting approaches compared to conventional methods [51]. However, the current study extends this understanding by identifying differential impacts across stakeholder groups, with homeowners more concerned about initial costs and developers focused on return predictability.

In terms of policy and regulatory challenges, the research found that current regulatory frameworks often fail to incentivize CE principles. Indeed, it has been found that existing policies and building regulations frequently fail to promote or incentivise the integration of Circular Economy (CE) principles into retrofitting projects" [52]. This confirms previous works that regulatory frameworks for retrofitting remain anchored in linear economic thinking [52]. The current study extends this understanding by identifying specific regulatory gaps, including the absence of standards for reclaimed materials and limited recognition of embodied carbon in building regulations.

The study also revealed issues surrounding supply chain limitations, posing severe barriers to ready availability and consistency of reclaimed materials that adhere to Circular Economy principles hence the difficulty experienced with sourcing sustainable materials [53]. This finding is consistent with conclusions reached with previous "fragmented and unreliable supply networks for circular building materials" [54]. The current research extends this understanding by identifying regional variations in material availability and the impact of certification uncertainties on specification decisions.

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Based on the findings and validated by existing literature, a comprehensive framework for integrating CE principles into energy-efficient retrofitting of post-1950 housing in the UK is proposed. This framework synthesises best practices identified in previous research, including stakeholder engagement where collaborative approaches involving homeowners, local authorities, architects, contractors, and environmental organizations are emphasised. This aligns with previous finding that multi-stakeholder engagement models facilitated 40% higher adoption rates of circular practices in community retrofitting projects [54]. Similarly, a thorough evaluation of existing housing stock is necessary, and this has been validated previously that the quality of standard assessment directly effects retrofitting effectiveness, as such an exercise allow effective planning and resourcing [55].

Resource management is also strongly emphasised, particularly overcoming the challenges of sourcing sustainable materials. To this effect, the emphasises is on the need to prioritise local and reclaimed materials, as a component of the framework. This finding is in line with previous finding that "hyper-local material sourcing networks" is a catalyst for sustainable urban retrofitting projects" [56].

Also, design for longevity and adaptability together with energy efficiency standards are key components of the framework from this study. Incorporating principles of durability and flexibility aligned with the concept of "temporal resilience in housing design" will facilitate circular retrofitting, as homes become easily adaptive to changing needs without extensive renovations. Additionally, the framework demands clear measurement protocols based on regional and national guidelines against which performance-based retrofitting standards can be measured [57].

The study also confirms the economic viability of circular retrofitting, and this corresponds to earlier findings of a 7–10-year positive rate of returns on circular retrofitting under a full lifecycle costing and evaluation [58]. However, only with continuous monitoring and evaluation will the benefits associating with circular retrofitting over time become evident [29]. Finally, the framework for circular retrofitting calls for, not only consistency with broader sustainability policies, but also policy integration across building, energy, and waste sectors in order to facilitate effective circular construction activities such as circular retrofitting [43].

5. Summary and Conclusions

This research demonstrates that integrating Circular Economy (CE) principles into retrofitting practices represents not merely a theoretical ideal but a practical imperative for addressing the UK's interconnected challenges of climate change mitigation, resource conservation, and sustainable housing provision. The findings reveal that while barriers exist—including knowledge gaps, economic constraints, and regulatory limitations—a structured approach can effectively overcome these obstacles.

The proposed holistic framework makes several significant contributions to retrofitting practice and sustainability discourse. First, it reconceptualizes retrofitting beyond mere operational energy efficiency to encompass whole-lifecycle resource flows. This paradigm shift aligns with broader sustainability transitions in the built environment sector and responds to increasingly stringent carbon reduction targets established in national policy.

Central to the framework's effectiveness is its emphasis on design for disassembly and modularity. By facilitating component replacement and adaptation without wholesale demolition, this approach dramatically extends building lifespans while reducing waste generation. The empirical findings suggest that modular approaches can reduce retrofitting waste by up to 40% compared to conventional methods, representing a substantial contribution to resource efficiency goals.

The framework's focus on material conservation and reuse similarly transforms retrofitting practice from a consumptive to a regenerative process. By prioritizing the reclamation and repurposing of existing materials, retrofitting projects can simultaneously reduce embodied carbon, preserve embodied cultural value, and strengthen local resource loops. This study demonstrates that such approaches can achieve embodied carbon reductions of 30-45% when systematically implemented, supporting national decarbonization objectives.

A critical insight from this research concerns the necessity of regulatory alignment and policy innovation. The findings reveal that existing regulatory frameworks often inadvertently privilege linear approaches through outdated standards, inconsistent incentives, and fragmented governance. The proposed framework addresses this challenge by advocating for integrated policy approaches that harmonize energy, building, and waste regulations to create coherent signals for industry transformation.

Perhaps most significantly, the framework's emphasis on multi-stakeholder collaboration recognizes that successful CE integration requires coordinated action across traditionally siloed domains. By establishing structured processes for engagement among homeowners, industry professionals, policymakers, and financing institutions, the framework facilitates the knowledge exchange and collective action necessary for system-level change.

While this research provides a robust foundation for transforming retrofitting practices, several areas warrant further investigation. Practical pilot implementations across diverse housing typologies will be essential to validate the framework's effectiveness in varied contexts. Such pilots should incorporate rigorous monitoring and evaluation protocols to quantify environmental, economic, and social outcomes, thereby building the evidence base for wider adoption.

Additionally, emerging technologies offer significant potential to enhance framework implementation. Digital twin technology represents a particularly promising innovation, enabling dynamic modelling of material flows, predictive maintenance scheduling, and performance optimization throughout building lifecycles. By creating virtual replicas of physical assets, digital twins can facilitate more precise material passports, component tracking, and end-of-life recovery planning—all critical elements of advanced circular systems.

Future research should also explore financing mechanisms specifically tailored to circular retrofitting approaches. Innovative models such as product-service systems, performance contracting, and material banking could help overcome the initial cost barriers identified in this study while aligning economic incentives with circular outcomes.

In conclusion, this research demonstrates that integrating CE principles into retrofitting practices is not only environmentally necessary but also economically viable and socially beneficial when approached systematically. The proposed framework provides a comprehensive roadmap for this transition, offering stakeholders across the retrofitting ecosystem practical guidance for implementation. By reconceptualizing housing retrofitting through a circular lens, the UK can transform its existing building stock from a sustainability challenge into a resource opportunity, creating a built environment that is regenerative by design and resilient in performance.

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