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Scaling Green Roof Retrofitting: Barriers, Enablers, and the Role of Circular Economy

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Abstract. Cities face increasing climate risks, requiring scalable solutions for urban sustainability. Green roof retrofitting offers environmental, economic, and wellbeing benefits, including stormwater management, urban cooling, and biodiversity enhancement. However, adoption remains limited due to financial constraints, regulatory fragmentation, technical feasibility concerns, and a lack of standardized lifecycle performance data. This study investigates the interdependencies among barriers and enablers influencing green roof retrofitting and explores whether circular economy principles can facilitate large-scale adoption. Using Interpretive Structural Modelling (ISM) and MICMAC analysis, the research structures these factors based on their driving power and dependence relationships, identifying critical leverage points for intervention. Preliminary findings from UK-based workshops and interviews with building owner-operators, contractors, and a sustainability consultant are presented. The analysis highlights key driving factors such as lack of performance and ROI data, supply chain maturity, conflicting regulatory requirements, availability of alternative financing, and sustainability incentives, while financial viability, tenant acceptance, property management, and innovation appetite emerge as dependent factors. Although circular economy strategies—such as modular systems, recycled materials, and service-based business models—offer potential to address key challenges, gaps in standards, regulatory clarity, and industry confidence may create additional barriers if not carefully managed.

1. Introduction

The world faces a complex climate and biodiversity crisis which threatens the future of all life on Earth (1,2,3,4). The majority of people globally now live in cities, and this is expected to rise to 66% by 2050 (5). Cities globally are polluted, hot, dry and impermeable (6). This means more people than ever will be experiencing more extreme, frequent and unpredictable weather events such as heatwaves and rainstorms (7).

Globally, there is a need to reduce carbon emissions (1) while simultaneously adapting to the impacts of climate change and restoring biodiversity and biodiverse habitats (9), for example by increasing use of circular economy materials (8). As cities across the UK and Europe face increasing climate risks and stringent carbon emission reduction targets, retrofitting existing buildings with green roofs offers a powerful strategy for urban resilience and sustainability (10).

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Green roofs contribute to carbon sequestration, energy savings, flood management, and biodiversity enhancement (11). However, despite these benefits, scaling up green roof retrofitting faces significant challenges, including technical, financial, regulatory and logistical barriers (12). In this study, green roof retrofitting refers to the installation of vegetated roofing systems on existing buildings not originally designed to accommodate them. It involves transforming conventional roofs into living ecosystems through the addition of waterproofing membranes, root barriers, drainage layers, growing media, and vegetation. This paper considers all types of green roofs in analysing the barriers and enablers associated with retrofitting.

While previous studies have identified barriers to green roof retrofitting, they often examine these factors in isolation. This paper explores the interdependencies among these green roof retrofitting barriers and enablers, while also assessing whether and how a circular supply chain model can facilitate widespread adoption. Using Interpretive Structural Modelling (ISM) and MICMAC analysis, this study maps the interdependencies among key challenges and opportunities, identifying critical leverage points for systemic change. Preliminary findings from interviews and workshops with building owner and operators, general and green roof contractors, and a sustainability consultant highlight priority areas for intervention, such as regulatory constraints, economic feasibility, and operational coordination across the value chain. By examining the interaction between circular economy practices and existing barriers or enablers, the research further provides insights into whether and how circularity could enhance scalability of green roof retrofitting. The results offer an emerging roadmap for policymakers and industry stakeholders to maximize the impact of green roof retrofitting.

2. Literature Review

2.1. Green Roofs and Retrofitting for Sustainability

As cities continue to grow, they face mounting challenges such as climate change, biodiversity loss, and worsening environmental conditions (13,14). Green roofs, a critical component of green infrastructure, provide multiple ecological, social, and economic benefits that help mitigate these urban issues. By absorbing rainwater, reducing runoff, and improving water quality, they play a crucial role in stormwater management (15). Additionally, green roofs help counteract the urban heat island effect (16), enhance air quality (17), and provide essential habitats for urban biodiversity (18). These multifunctional benefits align with the broader concept of nature-based solutions (NBS), which leverage natural processes to enhance urban resilience while promoting sustainability (19–21).

Given that buildings account for approximately 40% of global energy consumption and 36% of carbon emissions (23,24), improving their environmental performance is crucial for meeting net-zero targets. Retrofitting—modifying existing structures to enhance energy efficiency and sustainability—offers a viable strategy for reducing urban carbon footprints (22). Green roof retrofitting, in particular, has been recognized as an effective approach to improving building performance by reducing energy consumption, enhancing stormwater management, and contributing to urban cooling (25,26). Additional benefits include biodiversity enhancement through carbon sequestration (27) and extended roof lifespan due to protection from UV exposure (28).

Technological advancements have improved the feasibility of green roof retrofitting. The development of lightweight materials has made it possible to retrofit green roofs onto older buildings with limited load-bearing capacity while maintaining stormwater attenuation and thermal insulation benefits (32). Additionally, automated irrigation systems and smart

monitoring technologies have enhanced operational efficiency, ensuring optimal performance with minimal maintenance (33). Despite rapid growth in the green roof market—expanding by 17.1% annually in the UK to £30.7 million by 2016 (34) and reaching \$2.43 billion globally by 2024 (36)—green roof retrofitting remains underutilized. Germany, Switzerland, Austria, and Scandinavia have demonstrated higher adoption rates (34,35), but major gaps persist. London alone could retrofit 10 million square meters of roof space (35), while Europe's 2030 target for 5 square meters of green infrastructure per urban citizen highlights a €62 billion opportunity (35). These figures underscore the significant potential for scaling retrofitting strategies.

Despite the advantages and innovations, scaling up green roof retrofitting remains challenging due to technical, financial, and regulatory barriers (12). Retrofitting older buildings with green roofs often requires structural reinforcements, which can be expensive and logistically complex (38). The high initial costs deter building owners, while fragmented regulatory frameworks and a lack of clear incentives further slow adoption. Case studies, such as those from Stuttgart, highlight the multifunctionality and adaptability of green roofs, yet also reveal disparities in implementation due to varying policy environments and stakeholder priorities (37). These gaps suggest that a systematic approach is needed to integrate technological, financial, and policy-driven solutions for green roof retrofitting.

2.2. Circular Economy: A Potential Solution for Green Roof Retrofitting

One emerging strategy to overcome these challenges is the integration of circular economy principles into green roof retrofitting. The circular economy shifts away from the traditional "take-make-dispose" model and instead promotes resource efficiency through material reuse, recycling, and refurbishment. In the construction sector, circular practices may help address resource scarcity and reduce waste generation (29,30). Applying these principles to green roof retrofitting could lead to cost reductions, improved material efficiency, and increased feasibility for large-scale adoption. Examples of circular approaches in green roof retrofitting include using recycled substrates, modular green roof components, and repurposed materials to lower costs and environmental impact (31). However, despite growing interest, research on how circular economy principles can be effectively integrated into green roof retrofitting remains limited. Key questions remain regarding how to develop sustainable supply chains, create financial incentives, and measure the long-term benefits of circular retrofitting strategies.

2.3. The Need for Further Research

While substantial progress has been made in green roof technology, the challenge of scaling up retrofitting efforts remains unresolved. Current studies highlight the benefits of green roofs but often fail to address how the complex web of regulatory, financial, and supply chain barriers can be overcome. Furthermore, the potential of circular economy strategies to enhance green roof retrofitting remains underexplored, particularly in terms of supply chain development, financial viability, and performance evaluation. Given the urgent need for urban adaptation to climate change and the increasing pressure to meet carbon reduction targets, further research is needed to identify scalable strategies for green roof retrofitting including considering circular economy principles. Although previous research has explored the barriers to green roof retrofitting, few studies have examined how these challenges interact in a systemic way. The ISM-MICMAC methodology allows us to capture these relationships, prioritizing intervention points for maximum impact.

3. Methodology

This study employs Interpretive Structural Modeling (ISM) and MICMAC (Matrice d'Impacts Croisés Multiplication Appliquée à un Classement) analysis (39) to examine the interrelationships between factors influencing the adoption and scalability of green roof retrofitting. The research focuses on identifying key enablers and barriers as well as the dependencies among them, and questions whether a circular delivery model could support the adoption of green roof retrofitting.

The research follows a qualitative, expert-driven approach using a combination of semi-structured interviews and workshops. To explore the barriers and enablers of green roof retrofitting and to consider the potential impact of a circular economy framework on them, the paper draws on three key stakeholder perspectives: private building owner and operators, contractors, and sustainability consultants. The private building owner and operators represent the end-user perspective, offering insights into decision-making processes, financial considerations, and perceived benefits or risks of retrofitting. The contractor provides critical expertise on the practical feasibility of implementation, addressing technical constraints, supply chain challenges, and labor-related barriers. Lastly, the sustainability consultant emphasizes a holistic view encompassing a multidimensional view on enabling sustainability, integrating multidisciplinary knowledge of material flows, lifecycle sustainability, and regulatory frameworks that influence adoption at scale. Together, these perspectives capture a wide set of enablers and barriers as well as circular economy considerations, allowing for a structured analysis of interdependencies using Interpretive Structural Modeling (ISM) and MICMAC analysis.

The preliminary findings presented in this paper were collected through workshops with building owners and contractors (two organizations for each) and an in-depth interview with a sustainability consultant from a major consultancy firm. Workshops lasted three hours each; the interview, two hours. From these sessions, 12 to 15 key factors (i.e., enablers and challenges) were extracted per stakeholder group, addressing themes such as structural feasibility, different rooftop uses, financing, and policy. ISM was then applied to model the hierarchical relationships among these factors, using pairwise comparisons to construct a structured map of influence. ISM clarifies how complex and interlinked factors form layered dependencies, supporting strategic decision-making. MICMAC analysis followed, classifying each factor based on its driving power (ability to influence others) and dependence level (extent to which it is influenced). MICMAC organizes the factors into four categories—autonomous, dependent, linkage, and driving—revealing which variables are most influential in shaping the scalability of green roof retrofitting (39). Due to space constraints, only key driving (high influence) and dependent (highly influenced) factors are presented in the findings section, categorized by stakeholder group.

4. Findings

The analysis for building owner-operators identifies the key factors (see Table 1) with the highest driving power as: lack of performance and ROI data, maturity of the supply chain, conflicting regulations, sustainability requirements and incentives, availability of alternative financing options, and structural feasibility. Lack of performance and ROI data exerts strong driving power by creating uncertainty around the financial returns, operational benefits, and risk reduction associated with green roofs. Supply chain maturity also acts as a major driver, influencing access to reliable, high-quality, and innovative retrofit solutions, including those applying circular economy principles. Conflicting regulations, particularly tensions between fire safety, conservation requirements, and sustainability goals, complicate the retrofitting process and influence decision-making. Sustainability requirements and incentives, such as national carbon targets or planning frameworks promoting green infrastructure, act as important drivers by

encouraging adoption. Availability of alternative financing options, such as grants, service contracts, or green leases, helps address the challenge of high upfront costs. Structural feasibility—the physical ability of a building to support green roof installations—continues to play a significant role in shaping retrofit opportunities.

The factors with the highest dependence are ongoing financial viability, tenant willingness and acceptance, corporate ESG and sustainability goals, competing rooftop uses, property management, and innovation and risk appetite. These dependent factors are influenced by the driving factors. For example, the ongoing financial viability of a green roof depends on installation costs, maintenance burdens, and potential income streams. Tenant acceptance and corporate ESG goals are shaped by available incentives, demonstrable performance benefits, and alignment with broader sustainability frameworks. Competing rooftop uses, such as solar panels or mechanical plant equipment, and property management concerns depend on how financial and technical conditions are structured. Similarly, an organization’s willingness to pursue innovative or circular solutions depends on the maturity of supply chains and clarity of regulatory frameworks.

Table 1. Summary of key drivers and key dependent factors for building owner and operators

Factors with highest driving power	Factors with highest dependency
Lack of performance and ROI data	Tenant willingness & acceptance
Availability of alternative financing	Corporate ESG & sustainability goals
Conflicting regulations	Innovation & risk appetite
Sustainability requirements & incentives	Property management considerations
Supply chain maturity	Competing rooftop uses
Structural feasibility	Ongoing financial viability

From a building owner-operator perspective, the circular economy could play a role in mitigating some of these challenges by introducing innovative financing models, such as green roof leasing or service-based agreements, reducing the financial burden on building owners. Additionally, prefabricated, modular green roof systems using recycled materials could further improve the embodied carbon and some of the operational challenges. However, the lack of circular economy standards has been highlighted as a fundamental barrier to increasing adoption of circular approaches.

Contractors face both technical and financial hurdles when implementing green roof retrofitting (see Table 2). The lack of financial incentives and subsidies for installation is a key driving factor, making green roofs less attractive compared to other sustainability interventions. Unlike energy efficiency retrofits that receive funding from the government, green roofs lack widespread government support in the UK, placing a heavier financial burden on project developers. Another major driving factor is the local policy and planning gaps for green roofs in retrofitting. When it comes to green roofs, many local authorities focus on new builds rather than retrofit projects, leaving project teams without clear guidelines, incentives, or streamlined approval processes. This lack of regulatory clarity further complicates decision-making and slows adoption. The need for cost-benefit data also emerges as a critical driving factor. Decision-makers

often struggle to justify green roofs due to the lack of standardized economic and environmental impact assessments. Without clear projections on lifecycle savings, stormwater management benefits, and biodiversity gains, contractors face difficulties convincing clients and stakeholders to invest in green roof retrofitting.

On the dependent side, upfront cost focus over lifecycle benefits remains a major limitation. Many projects prioritize short-term affordability, disregarding long-term energy savings, roof lifespan extension, and environmental benefits. Contractors often struggle to shift mindsets from initial capital costs to a holistic cost-benefit perspective. Additionally, maintenance challenges act as a dependent factor, as uncertainty around who is responsible for long-term care leads to reluctance in adopting green roofs. Without clear service contracts or maintenance models, clients hesitate to commit to these solutions. Lastly, value engineering and cost-driven cuts often lead to green roofs being removed from projects. When budgets tighten, green roofs are among the first to be sacrificed, reinforcing the need for stronger policy mandates and financial incentives to ensure green roofs remain a priority.

Table 2. Summary of key drivers and key dependent factors for contractors

Factors with highest driving power	Factors with highest dependency
Lack of financial incentives and subsidies for installation	Upfront cost focus over lifecycle benefits
Local policy and planning gaps for green roofs in retrofitting	Maintenance challenges
Need for cost-benefit data	Value engineering & cost-driven cuts

From a contractor point of view, the circular economy could play a role in overcoming these challenges by promoting innovative financing models, such as performance-based contracts, which shift the cost burden away from upfront investments and onto long-term savings. Additionally, modular green roof systems using recycled materials could streamline installations and maintenance, improving affordability and long-term stewardship concerns. However, stronger policy support and regulatory adjustments are needed to ensure these solutions can be integrated effectively. Challenges related to recycled materials, end-of-life management, and compliance hurdles limit the use of innovative components and approaches in green roof retrofitting. Many innovative solutions face regulatory roadblocks, with fire safety, toxicity concerns, and durability uncertainties preventing widespread market adoption.

The sustainability consultant emphasized the need for lifecycle data and benchmarks for holistic cost-benefit analysis as a primary driving factor. Without standardized methodologies for measuring the economic, social, and environmental benefits of green roofs, decision-makers struggle to justify investments. Establishing consistent lifecycle assessment frameworks would help improve green roof retrofitting. Another key driving factor is the decarbonization and EPC-driven funding priorities in the UK. Public funding is often directed toward energy efficiency upgrades, such as insulation or heat pumps, rather than biodiversity-focused solutions like green roofs. This funding disparity limits green roof adoption for retrofitting despite their positive impact on multiple sustainability issues. Additionally, the lack of knowledge dissemination and training, along with a shortage of innovative case projects, emerges as a major driving factor. Many architects, engineers, and developers lack direct experience and/or confidence with green roof

retrofitting, leading to hesitancy. Expanding demonstration projects and industry training could bridge this knowledge gap.

On the dependent side, value engineering and cost-driven cuts frequently remove green roofs from retrofitting projects. Since the financial returns are not clear (see the driving factors), they are often sacrificed in favor of more traditional sustainability measures. Similarly, it seems that the reason certification schemes (such as BREEAM or WELL) are the primary adoption drivers is a result of knowledge gaps, lack of lifecycle data and incentives. Without direct financial incentives, this reliance on certification frameworks slows widespread adoption as they don't have a high driving power. Other dependent factors include the short-term investment mindset, where many stakeholders prefer solutions with faster financial payback periods, and the lack of better streamlined supply models, as fragmented procurement processes complicate green roof implementation.

Table 3. Summary of key drivers and key dependent factors for sustainability consultants

Factors with highest driving power	Factors with highest dependency
Need for lifecycle data & benchmarks for holistic cost-benefit analysis	Value engineering & cost-driven cuts
Decarbonization and EPC-driven funding priorities	Certification schemes as primary adoption drivers
Lack of knowledge dissemination & training and innovative case projects	Short-term investment mindset
	Lack of streamlined supply models

It was stated that the circular economy could play a role by introducing integrated green roof service models, where design, installation, and maintenance are bundled under long-term contracts. Additionally, circular material certification and clearer lifecycle assessments could strengthen financial justification, making green roofs a more competitive solution for retrofitting.

5. Discussion

A recurring challenge across all stakeholder groups is the high upfront cost of green roof retrofitting and the lack of financial incentives. The MICMAC analysis underscores that both contractors and building owner-operators perceive financial viability as highly dependent on upstream factors, while sustainability consultants emphasize the systemic absence of funding mechanisms that prioritize green roofs over other sustainability measures. Regulatory fragmentation, particularly tensions between fire safety, conservation, and sustainability requirements, further complicates adoption. Moreover, a lack of clear lifecycle performance data and standardized evaluation metrics leads to uncertainty regarding green roofs' financial and environmental value, deterring investment.

The findings reveal that many perceived barriers and enablers are in fact dependent on a smaller number of key driving factors. For example, ongoing financial viability is heavily influenced by availability of alternative financing options, supply chain maturity, and performance data. Similarly, the maturity of the green roof supply chain and the presence of sustainability incentives shape broader adoption conditions across stakeholder groups. This distinction is

critical, as it suggests that targeting core drivers—such as financing models, regulatory coherence, and lifecycle data standardization—can have a systemic impact.

While circular economy principles offer potential to address some of these systemic drivers, they could also introduce new complexities. For instance, requirements for recycled material standards, end-of-life planning, or innovative modular systems could create additional regulatory or supply chain hurdles if not managed carefully. A more balanced, phased integration of circular economy approaches is therefore recommended, focusing initially on areas where clear benefits align with existing regulatory frameworks and market capabilities. Key implications include:

- Targeted Financial Support – Green roof retrofitting remains financially challenging due to high upfront costs and limited incentives. Expanding funding mechanisms—such as grants, tax credits, or performance-based subsidies—could improve economic feasibility and reduce financial risk for building owner/operators.
- Regulatory Coherence & Incentives – Misalignment between national sustainability policies and local planning or fire regulations complicates green roof adoption. Clearer guidelines, streamlined approval processes, and policy integration across government levels could remove regulatory bottlenecks.
- Standardized Performance Metrics & Data – A lack of consistent ROI and environmental performance data hinders investment confidence. Establishing industry-wide benchmarks for lifecycle costs/benefits would provide clearer justification for adoption.
- Knowledge & Best Practice Sharing – Limited familiarity with green roof retrofitting and its innovative applications lead to hesitation in adoption. Expanding industry training, knowledge-sharing platforms, and case study demonstrations could build confidence.
- Shifting Investment Mindsets – The dominance of short-term cost considerations leads to green roofs being deprioritized in retrofitting projects. Promoting lifecycle-based decision-making, demonstrating long-term financial and environmental benefits could shift perspectives.

6. Conclusion

This study provides new insights into the interdependencies among the barriers and enablers of green roof retrofitting while considering the potential role of circular economy strategies in supporting adoption. A central finding is the importance of distinguishing between core driving factors—such as availability of financing options, regulatory clarity, and supply chain maturity—and the dependent factors that result from them, such as ongoing financial viability and tenant willingness. Addressing core drivers could create a more enabling environment for scaling up green roof retrofitting. In particular, establishing standardized performance metrics and lifecycle cost-benefit frameworks would strengthen the financial case for investment. Policy coherence across fire safety, conservation, and sustainability priorities will be equally crucial.

Although circular economy strategies—such as modular prefabricated systems, recycled material use, and integrated service models—offer promising ways to improve cost-effectiveness and environmental performance, their implementation must be carefully managed to avoid creating additional regulatory or supply chain barriers. Stronger policy support, pilot projects, and clearer certification pathways will be essential to successfully integrate circularity into mainstream retrofitting practices. This study acknowledges its limitations, particularly its focus on the UK context and the relatively small number of stakeholder participants. Future research should validate these preliminary findings through broader stakeholder engagement and explore practical demonstration projects to assess scalable circular green roof retrofitting models.

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