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Systematic Review

A System Thinking Approach to Circular-Based Strategies for Deep Energy Renovation: A Systematic Review

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Abstract: Over 85% of buildings in the European Union were constructed before 2001, contributing to energy inefficiencies, material waste, and increasing socio-economic disparities. While deep energy renovations (DER) are critical to EU climate goals, their implementation remains hindered by financial, regulatory, and social barriers. Integrating circular economy (CE) principles into DER offers a pathway to enhance resource efficiency and sustainability yet requires a systemic understanding of feedback dynamics. This study applies a systems-thinking approach to examine the interdependencies influencing CE-DER implementation. Five thematic clusters—technical enablers, economic and policy barriers, social sustainability factors, environmental considerations, and digitalization for climate resilience—are identified, informing the development of causal loop diagrams (CLDs). The CLDs reveal key reinforcing loops such as innovation investment, policy learning, stakeholder co-design, operational efficiency, and balancing loops, including certification bottlenecks, financial fragmentation, and digital resistance. The findings suggest that CE-DER success relies on activating reinforcing dynamics while addressing systemic constraints through coordinated financial incentives, ethical digitalization, and inclusive governance. By visualizing interdependencies across technical, social, and policy domains, the feedback-oriented framework developed provides actionable insights for advancing socially equitable, resource-efficient, and climate-resilient renovation strategies.

Keywords: deep retrofit; housing energy efficiency; building performance; policy fragmentation; causal loop diagram

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1. Introduction

The European Union's (EU) aging building stock presents a major challenge in achieving climate neutrality by 2050. Over 85% of buildings in the European Union were constructed before 2001, contributing to energy inefficiencies, material waste, and increasing socioeconomic disparities [1]. Many of these buildings exhibit structural defects such as leaking roofs, dampness, and poor insulation, negatively affecting occupants' health, well-being, and economic stability, particularly for vulnerable communities [2]. Furthermore, the urgency of addressing energy inefficiency in buildings has been heightened by the increasing severity of climate change, which exacerbates extreme weather conditions like heat waves and cold spells, placing additional strain on building energy demand for heating and cooling. Additionally, during recent years, energy market instability has further affected household's spending capacity, widening the energy poverty issue outside the traditional very low-income user's boundaries. These challenges are deepened by the fact that most EU member states have yet to implement holistic, integrated policies that address the interplay of energy efficiency, affordability, and climate adaptation [3,4].

Deep energy renovation (DER) has emerged as a key strategy for improving energy efficiency and strengthening climate resilience. Although the EU does not formally define deep renovation, it is associated with at least a 60% reduction in primary energy consumption, achieved through building envelope upgrades, HVAC modernization, and the integration of renewable energy sources [5]. These measures significantly reduce emissions and energy costs while delivering broader socio-economic benefits, such as improved housing affordability, lower energy poverty, improved livability and comfort conditions, reduced health risks and job creation in construction and energy sectors. Recent studies highlight that DER projects that incorporate circular economy (CE) principles such as material reuse, extended building lifespans, and design for disassembly can further enhance sustainability outcomes by reducing construction waste and embodied carbon emissions [6,7]. Material circularity strategies in DER have shown potential for reducing raw material extraction and supply chain emissions, aligning with EU resource efficiency objectives [8]. However, studies suggest that energy efficiency measures alone may not sufficiently address broader issues such as social equity and just transition principles, which are necessary for ensuring inclusive renovation processes [9,10].

The renovation rates remain critically low, currently just 0.2% per year, far below the 3% target needed to meet EU goals [11]. The main barriers include fragmented renovation approaches that focus on isolated technical solutions while overlooking social, economic, and environmental interdependencies [12]. The research indicates that financial barriers, coupled with regulatory inconsistencies, act as primary obstacles to renovation uptake, particularly in private rental housing, where landlords have little incentive to invest in efficiency upgrades [13]. As a result, the most vulnerable populations often remain underserved by renovation policies, further deepening social inequalities and reducing the overall effectiveness of sustainability interventions [3].

Beyond energy inefficiency, the EU's building sector is also a major contributor to resource depletion and waste generation. The construction sector accounts for 52% of the EU's material footprint and generates 37% of its total waste, with less than 40% being recycled [14]. Additionally, 20 to 25% of total building-related emissions stem from embodied carbon in materials, underscoring the environmental burden of traditional construction and renovation practices [15]. Studies indicate that the policy framework often overlooks the embodied carbon footprint of building renovations, despite its long-term climate impact [16,17]. Circular strategies not only reduce environmental impact but also create local employment, strengthen economic resilience, and foster socially inclusive renovation processes [18]. However, the practice implementation of circular principles in building renovation is still in its infancy, constrained by material certification requirements and the lack of standardized methodologies for assessing circularity performance.

Despite their potential, Circular Economy (CE) and deep renovation strategies remain disconnected in research and policy [19]. While deep renovation focuses primarily on reducing operational energy use, it often neglects material efficiency, embodied emissions, and lifecycle impacts [20]. Coupling CE with DER is crucial for a comprehensive sustainable approach. It reduces operational to and embodied emissions, increases cost-effectiveness, and closes resource loop to avoid unnecessary material extraction [21]. However, these principles remain largely absent in current renovation frameworks [12].

However, researchers have also shown concerns about higher upfront costs, regulatory challenges, and the complexity of implementing circular principles in existing building stock [6]. Without systemic integration, current efforts will remain fragmented, failing to drive the transformative changes necessary to meet the EU's climate and energy goals. This gap highlights the need for a systems-thinking approach, that moves beyond linear renovation models and fosters synergistic relationships between energy efficiency, material circularity, and social sustainability.

This paper critically examines how circular economy (CE) principles can strengthen Deep Energy Renovation (DER) in the EU's built environment by addressing social sustainability, resource efficiency, and systemic policy integration. Using a systems-thinking approach, it explores the barriers, enabling conditions, and policy gaps that hinder the effective adoption of CE strategies in large-scale renovations. Moving beyond isolated technical solutions and siloed approaches, Systems thinking provides a framework for understanding the complex interconnections between technical, economic, social, and regulatory factors that influence energy renovation outcomes. Unlike traditional linear approaches, which assess interventions in isolation, systems thinking emphasizes interdependencies, highlighting how different elements within the renovation ecosystem interact over time [22].

The study also assesses socio-technical interactions contributing to the persistence of linear renovation models, offering insights into how policies and stakeholder dynamics influence implementation. To bridge existing gaps, it investigates the interconnections between energy efficiency, social equity, and circular resource management while identifying pathways for integrated, community-driven renovation strategies that align with the EU's 2050 climate neutrality goals.

Two key research questions are addressed:

1. How can circular economy principles enhance the effectiveness and long-term sustainability of deep energy renovations in the EU?
2. What are the key barriers and enabling factors for integrating circular economy principles into deep energy renovation policies and practices?

By exploring existing knowledge and identifying key interdependencies, this analysis provides actionable insights for policymakers, researchers, and industry stakeholders on advancing socially equitable, economically viable, and environmentally sustainable renovation models. The findings aim to contribute to the EU's broader objectives of climate neutrality, energy justice, and resource-efficient urban development, ensuring that future renovation strategies are both technically effective and socially inclusive.

2. Materials and Methods

This study examines the integration of CE principles within the fragmented landscape of DER in the EU. It employs a structured review process to detect interdependence, barriers, and enablers within CE embedded energy renovation strategies. The PRISMA (Preferred Reporting Items for Systematic Reviews and Meta-Analyses) framework was adopted to guide the review process and to ensure methodological transparency and replicability. The review protocol is registered with the International Prospective Register of Systematic Reviews (PROSPERO) under CRD42024562215. Keywords were derived from the research questions and thematic analysis of the existing scientific research and policy documents to ensure the coverage of key concepts.

The keywords were chosen based on:

- Primary concepts from research question (e.g., Circular Economy, Deep Energy Renovation, Energy Efficiency).
- Synonymous and related terms to address variations in terminology, as detected in key policies and the literature (e.g., "Building Retrofitting" for Deep Renovation, "Material Reuse" for Circular Economy).
- Boolean operators are applied to refine the search and improve relevance.

As illustrated in (Figure 1), the study follows a three-stage structured literature review process to ensure a transparent and comprehensive assessment of how CE principles can enhance energy renovations.

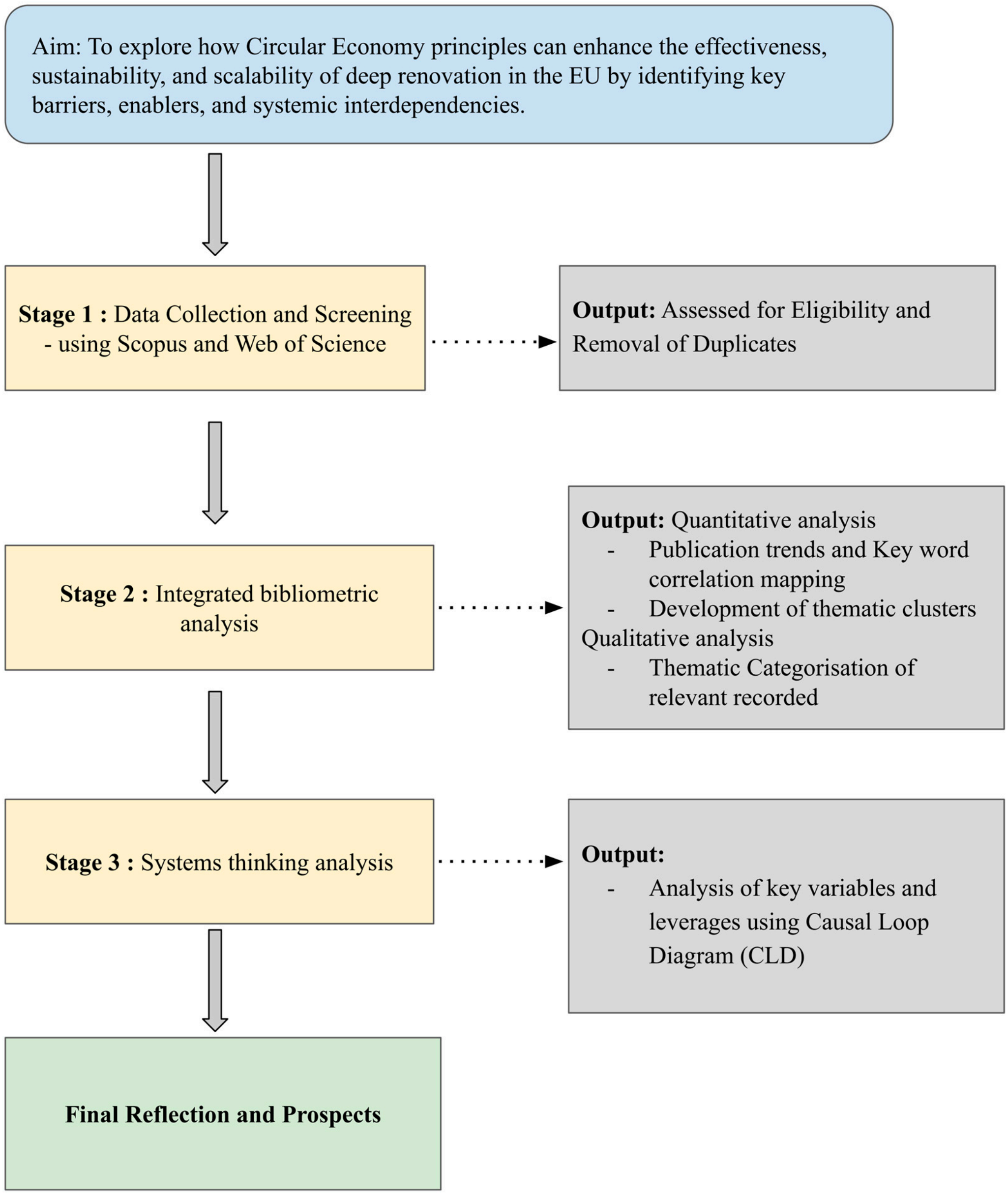

Figure 1. Workflow diagram outlining the review process.

In stage 1, a structured data collection and screening process was conducted using web databases for a scientific literature review. A predefined keyword-based search strategy with Boolean operators to ensure comprehensive coverage was applied to extract relevant peer-reviewed studies. The initial dataset underwent duplicate removal followed by title and abstract screening, and full-text eligibility assessment based on predefined inclusion and exclusion criteria, ensuring that only peer-reviewed, high-quality studies were considered for further analysis.

Stage 2 involves a quantitative bibliometric analysis aimed at examining research trends, dominant themes, and interdisciplinary gaps in Circular Economy (CE) and Deep Energy Renovation (DER) literature. This phase systematically analyzed peer-reviewed studies, evaluating publication patterns, keyword co-occurrence networks, and thematic distributions. Bibliometric mapping was conducted using VOSviewer [23], which facilitated keyword clustering, citation network analysis, and co-occurrence mapping to identify key research trajectories.

The qualitative thematic synthesis categorized the reviewed studies into five thematic clusters, structured around keyword link strength, thematic relevance, and interdisciplinary connections. This classification provided a systematic framework to analyze knowledge gaps and fragmentation within CE-DER research. The integration of quantitative and qualitative bibliometric methods in this stage established a cohesive foundation for the next phase, which applies systems thinking to assess deeper interdependencies within the research landscape.

Stage 3 builds on the bibliometric analysis from Stage 2, a systems thinking approach was employed to capture the complex interactions among technical, economic, social, environmental, and policy dimensions that influence CE adoption in DER. Unlike traditional linear methodologies, which assess barriers and enablers in isolation, systems thinking provides a holistic perspective, enabling a structured categorization of challenges and interconnections across thematic clusters.

The five thematic clusters identified in Stage 2, based on keyword co-occurrence, thematic relevance, and interdisciplinary linkages served as the framework for qualitative synthesis. Interdependencies within and across these clusters were mapped, revealing feedback mechanisms that either reinforce or stabilize CE-driven DER implementation.

A key tool in the system's thinking is the Causal Loop Diagram (CLD), which visually maps the relationship between key variables and identifies feedback loops within the system [24,25].

The CLD (Figure 2) consists of the following:

- **Variables,** represent critical factors influencing CE-DER adoption (e.g., financial incentives, material reuse, etc.)
- **Arrows,** indicate the causal relationships between the variables.
- **Polarities,** defining whether they are reinforcing (+) (amplifying effects over time) or balancing (-) (counteracting effects to stabilize the system).

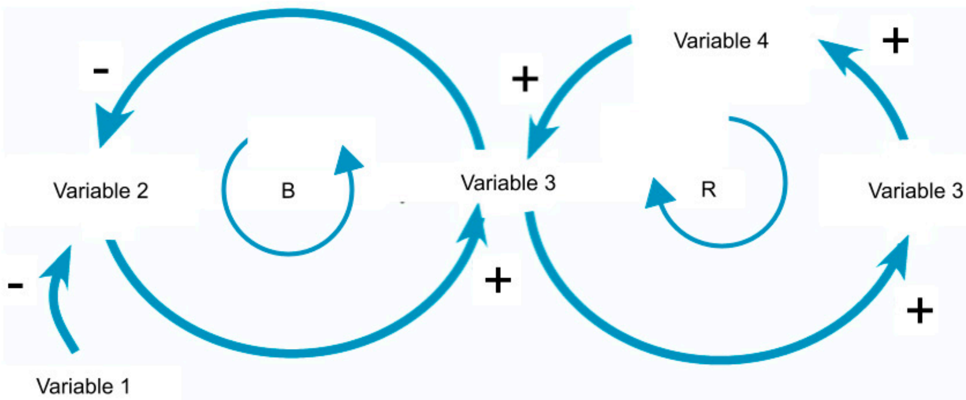

Figure 2. CLD basic structure.

Therefore, a CLD is applied to highlight possible interconnection and contrast that might have hampered progress in CE-DER so far. These were developed and created using Vensim software (Vensim 10.3.0) [26] facilitating the systematic identification of reinforcing and balancing loops, bottlenecks, and leverage points [24].

The systems mapping exercise incorporated stakeholder interactions, social dynamics, behavioral patterns, and regulatory influences alongside technical and financial factors. The insights helped bridge research and policy gaps, supporting the development of inclusive, adaptive, and resilient renovation strategies aligned with the EU's climate and sustainability goals.

Data Collection and Screening—Literature Search Strategy

The literature search was conducted using Scopus and Web of Science (WoS), two widely recognized databases in bibliometric research [27,28]. These platforms were chosen for their comprehensive coverage and structured filtering tools. Other platforms such as ScienceDirect, ResearchGate, and Google Scholar—were considered but excluded. ScienceDirect largely overlaps with Scopus, making its inclusion redundant. ResearchGate functions as a voluntary repository and may have outdated or non-peer-reviewed content. Google Scholar aggregates a wide range of sources, including grey literature and magazine articles, but lacks adequate tools for filtering and selecting scholarly items. Despite the inclusion of such contributions that might have improved policy insights, the choice is to keep sources strictly adherent to verify scientific journals where contents entered a review process before being published to avoid or at least reduce the risk of introducing non-reliable pieces of information.

In contrast, Scopus and WoS provide access to peer-reviewed records curated by independent entities, ensuring methodological rigor and reliability. To ensure a comprehensive yet targeted selection of the relevant literature, this study applied a structured keyword selection strategy based on the 3W framework (What, Who, and Where) Table 1. In addition, Boolean operations were applied to construct effective search strings and enhance the precision of the database queries.

Table 1. The 3W framework and corresponding keywords.

3W Framework	Keywords Used in Boolean Search
What? (Key thematic concepts: Circular Economy and Energy Renovation)	"Circular Econo* OR "Circular const*" OR "Material re*" OR "Resource efficiency" OR "Net Zero" AND "Deep Reno*" OR "Energy Retrofi*" OR "Energy efficien*" OR "Building renov*" OR "Sustainable construction" OR "Low-carbon buildings"
Who? (Relevant stakeholders: Policymakers, professionals, building occupants and other key actors)	"Stakeholder*" OR "Tenants" OR "Building owners" OR "Urban planners" OR "Policy makers" OR "Construction industry"
Where? (Targeted built environment: Housing and existing building stock)	"Housing" OR "Apartment*" OR "Social housing" OR "Public housing" OR "Existing buildings"

To refine the results further, exclusion terms were applied to eliminate studies that focused on industrial circular economy, manufacturing, or agriculture, as they fall outside the scope of the built environment. Additionally, rural settings were excluded to maintain the research's focus on urban renovation strategies. The exclusion criteria included:

(NOT "Indust circular economy" OR "Manufac*" OR "Agri*") AND (NOT "Rural*")

Based on this structured approach, the final search string was developed as follows:

(("Circular Econo*" OR "Circular const*" OR "Material re*" OR "Resource efficiency" OR "Net Zero") AND ("Deep Reno*" OR "Energy Retrofi*" OR "Energy efficien*" OR "Building renov*" OR "Sustainable renovation" OR "Low-carbon buildings")) AND ("Stakeholder*" OR "Tenants" OR "Building owners" OR "Urban planners" OR "Policy makers" OR "Construction industry") AND ("Housing" OR "Apartment*" OR "Social housing"

OR "Public housing" OR "Existing buildings") NOT ("Indust* circular economy" OR "Manufac*" OR "Agri*") NOT ("Rural*").

The final search string was applied across each database's titles, keywords, and abstracts. Since research area classifications differ between Scopus and Web of Science, filters were carefully tailored to each platform to ensure consistency and alignment with the study's objectives. Conference papers, reports, and non-peer-reviewed sources were excluded to maintain academic rigor and methodological reliability. The following filters were applied to narrow down the search:

- Years: 2015–2025 (ensuring that the focus remained on recent advancements in the field of circular economy and deep energy renovations)
- Language: English.
- Types of work in WoS: articles, review articles and book chapters.
- Types of work in Scopus: articles, reviews, and book/book chapters.
- Research area: there are differences between WoS and Scopus, as shown in Table 2 below.

Table 2. Selected categories in WoS and Scopus databases.

Database	Relevant Research/Subject Areas
Web of Science (WoS)	Environmental Sciences and Ecology Construction and Building Technology Engineering Energy and Fuels Architecture Urban Studies and Regional Planning Green Sustainable Science and Technology
Scopus	Energy Environmental Science Social Science Engineering

The systematic review was conducted between December 2024 and March 2025 with regular updates throughout the process. Following PRISMA guidelines, the article selection process was documented in a structured, transparent manner, as shown in Figure 3.

An initial database search across Web of Science (WoS) and Scopus retrieved 1005 records. To eliminate duplicates, a combination of automated filtering via Mendeley and manual screening was applied, reducing the dataset to 605 unique studies.

During the first screening phase, titles and keywords were evaluated against strict inclusion and exclusion criteria to ensure relevance and quality. This led to the exclusion of 300 studies, primarily due to misalignment with the research scope, scale mismatch, access limitations, or thematic misalignment.

The remaining 305 studies underwent an abstract-level eligibility assessment, resulting in the removal of 106 additional studies due to methodological limitations, insufficient empirical data, or lack of direct relevance to Circular Economy and Deep Renovation (CE-DR) integration. A full-text review was conducted for 199 records, resulting in the exclusion of 100 studies due to inaccessible full texts or misalignment with the study's systems-thinking focus. A total of 99 high-quality, peer-reviewed studies were included in the final review, forming the foundation for thematic analysis and synthesis.

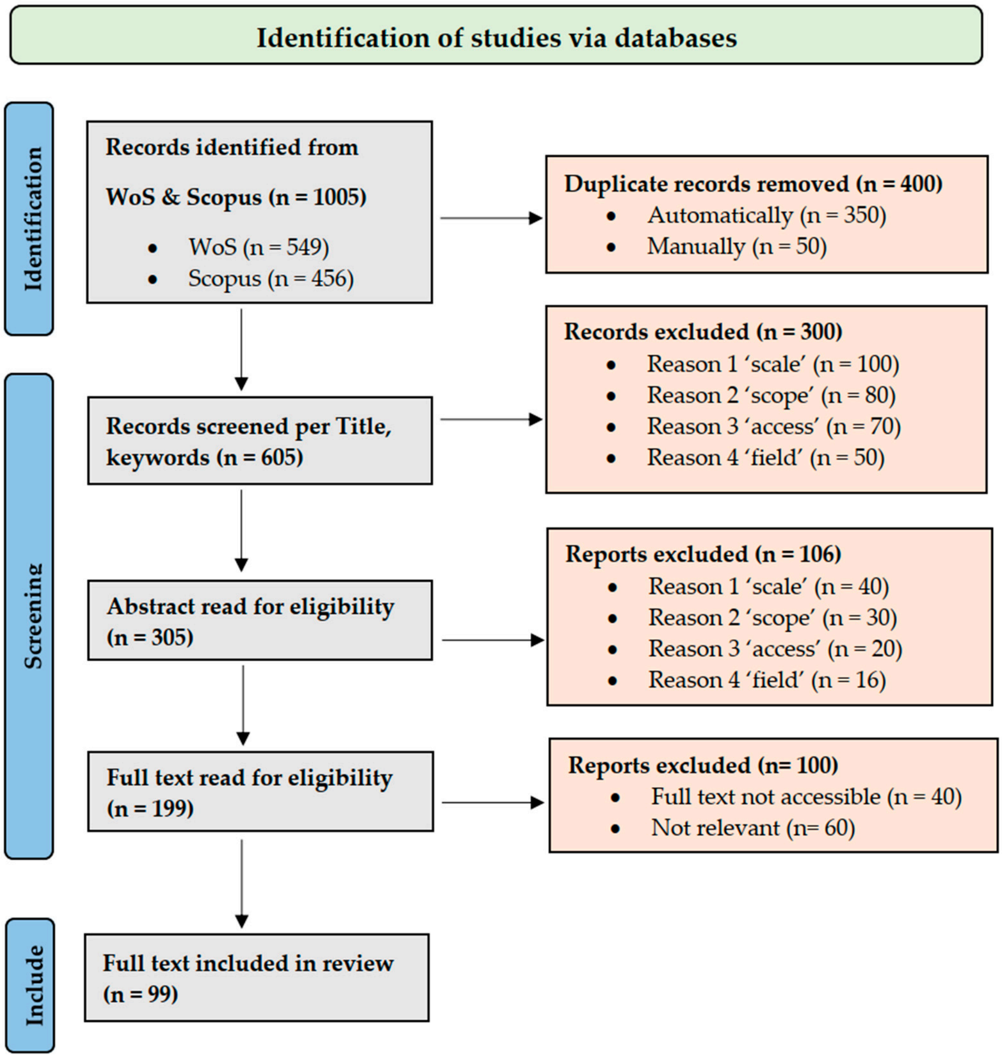

Figure 3. PRISMA flow diagram showing the systematic literature selection process, including records identified, screened, assessed for eligibility, and included in the review.

3. Results

This section presents the outcome of stage 2 integrating quantitative and qualitative bibliometric analyses to examine how Circular Economy (CE) principles are embedded in Deep Energy Renovation (DER).

3.1. Integrated Bibliometric Analysis

A bibliometric analysis was conducted on the 99 selected peer-reviewed studies from 2015 to 2025 to assess publication trends, keyword co-occurrence networks, and thematic distributions. While the qualitative thematic synthesis explores systemic interdependencies, barriers, and enablers in CE-DER research. Findings show that academic engagement with CE-DER has significantly increased post-2020, aligning with key European policies such as the European Green Deal (2019), the Renovation Wave (2020), and updates to the Energy Performance of Buildings Directive (2021) [29,30]. However, despite this growth, research is still imbalanced, with technical advancements dominating the discourse while economic, social, and policy dimensions are underexplored.

To systematically classify CE-DER research, a bibliometric mapping of peer-reviewed studies was conducted, identifying the following five thematic clusters:

1. Technical Enablers;

2. Economic and policy barriers;
3. Social Sustainability Factors;
4. Environmental Considerations;
5. Digitalization and Data-Driven Systems for Climate Resilience.

These clusters structure the subsequent qualitative synthesis and provides a data-driven assessment of research gaps and interconnections.

Bibliometric Mapping and Publication Growth

A bibliometric analysis of peer-reviewed studies from 2015 to 2025 reveals an exponential increase in research output after 2020, showing a direct correlation between policy frameworks and academic engagement (Figure 4). Before 2019, publications addressing CE integration in DER were scattered and fragmented, but after 2020, the research volume increased sharply, driven by policy-driven decarbonization efforts.

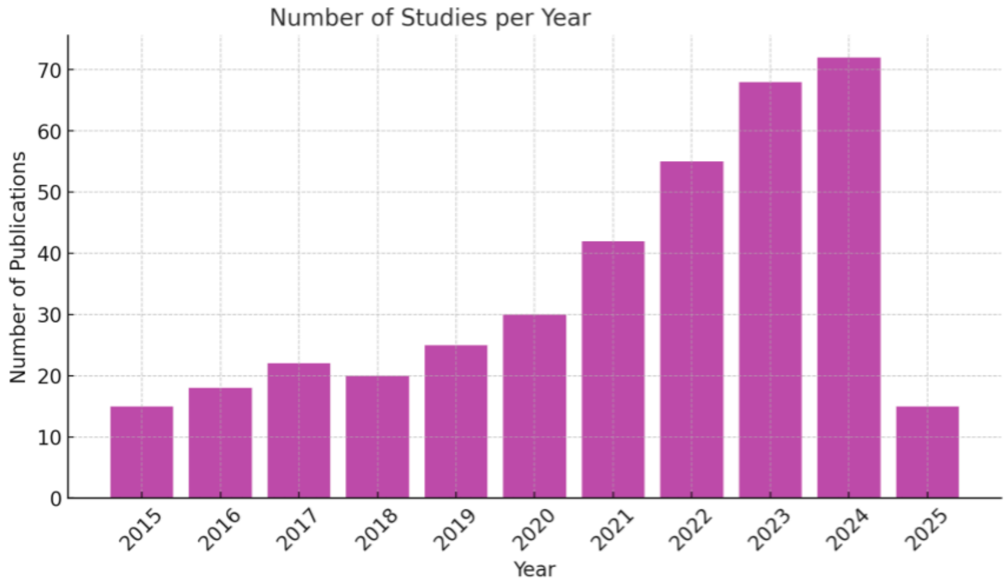

Figure 4. Annual publication distribution from 2015 to 2025.

A keyword co-occurrence analysis using VOSviewer [23] (Figure 5) helped identify dominant research themes and interdisciplinary gaps. A minimum occurrence threshold of five was applied to include only the most relevant and recurring terms, and the association strength normalization method was used to measure link strengths. The resulting keyword network was used to generate co-occurrence maps, with visual clustering performed using VOSviewer's built-in modularity-based clustering algorithm. Frequently occurring keywords such as "energy efficiency", "lifecycle assessment", and "residential buildings" indicate that research is primarily focused on building performance optimization. However, weaker linkages between financial mechanisms, policy incentives, and social justice concerns highlight critical knowledge gaps [18,31].

Distribution of Records Across Thematic Clusters

To provide a structured categorization of research, studies (n = 99) were classified into five thematic clusters based on keyword co-occurrence strength, interdisciplinary connections, and research scope Table 3. The distribution of records illustrates the dominance of technical research while also highlighting the underrepresentation of economic and social aspects in CE-DER literature. This classification provides a structured foundation for the integrated analysis of each thematic cluster, ensuring coherence between bibliometric insights and qualitative thematic synthesis.

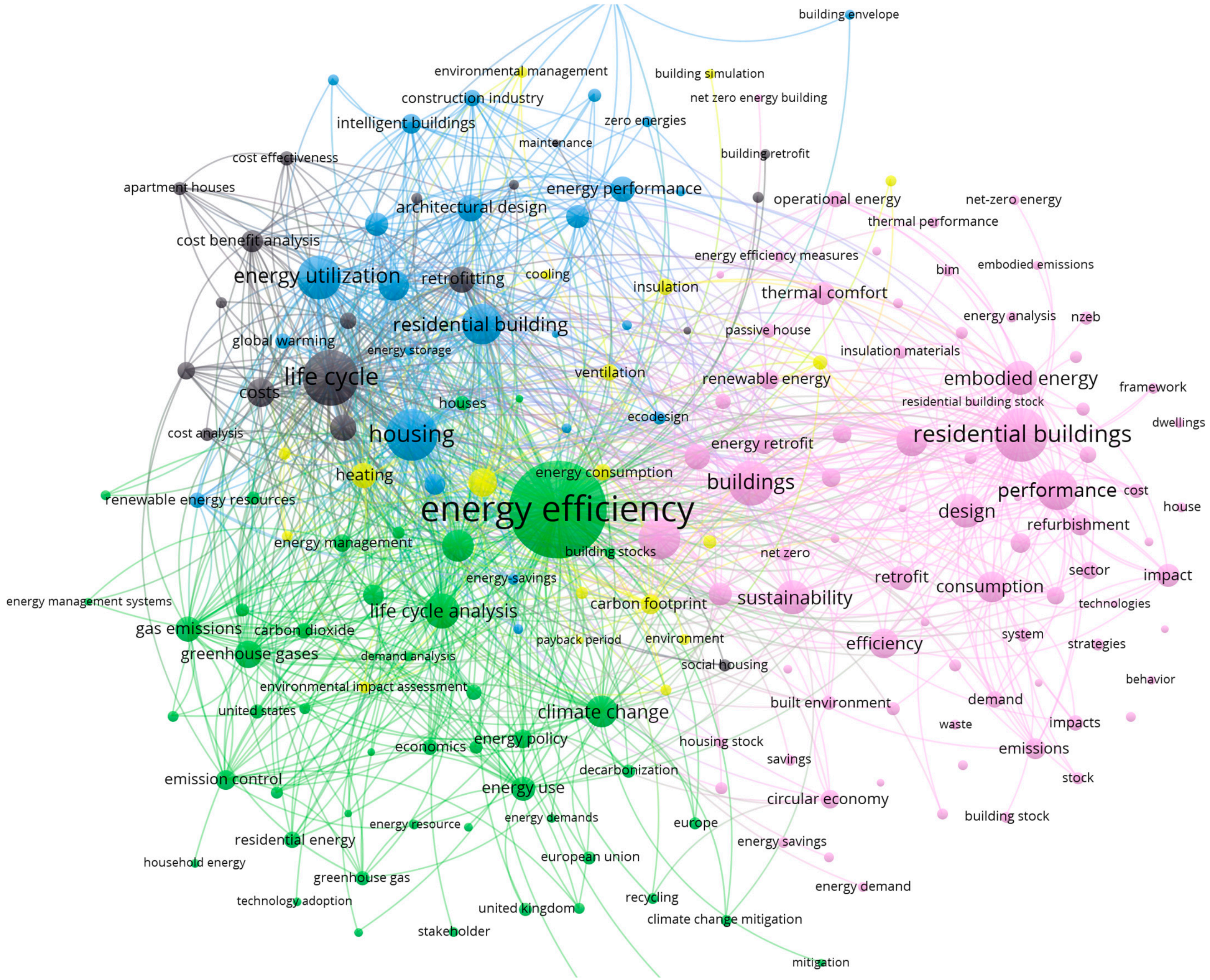

Figure 5. Network analysis—keyword co-occurrence map. Generated using VOSviewer Software (version 1.6.20).

Table 3. Distribution of records per thematic cluster.

Clusters	Relevant Records
Technical Enablers	Sánchez Ramos et al., 2019 [31]; Wu et al., 2017 [32]; Storck et al., 2023 [33]; Passoni et al., 2022 [8]; Antonov et al., 2021 [34]; Antonov et al., 2020 [35]; Kuusk and Kalamees, 2016 [36]; Abbà et al., 2024 [37]; Dey et al., 2023 [38]; Gubert et al., 2023 [39]; Nigumann et al., 2024 [40]; Niemelä et al., 2017 [41]; Walker et al., 2022 [42]; Seo and Foliente, 2021 [43]; Szymańska et al., 2022 [44]; Sáez-de-Guinoa et al., 2022 [12]; Ma'bdeh et al., 2023 [45]; Kaewunruen et al., 2019 [46]; Lingard, 2021 [47]; Österbring et al., 2019 [48]; Attia et al., 2017 [49]; Moran et al., 2020 [50]
Economic and Policy Barriers	Fabbri et al., 2023 [51]; van der Schoor, 2022 [30]; Singh et al., 2019 [52]; Triantafyllopoulos, 2024 [53]; Lassandro et al., 2024 [54]; Jerome et al., 2021 [55]; Palladino, 2023 [56]; Ruggieri et al., 2023 [3]; Prabatha et al., 2023 [57]; Capelo et al., 2023 [58]; Barrella et al., 2023 [59]; Tingey et al., 2021 [60]; Konstantinou et al., 2020 [61]; Toleikyte et al., 2018 [62]; Horvath, 2017 [18]; Filippidou et al., 2017 [63]; Copiello et al., 2017 [64]; Thomas et al., 2024 [19]

Table 3. *Cont.*

Clusters	Relevant Records
Social Sustainability Factors	Mohareb et al., 2022 [65]; Marchi et al., 2023 [66]; Lucchi and Delera, 2020 [67]; Marchi and Gaspari, 2023 [68]; Shwashreh et al., 2024 [69]; Omar & Galal Ahmed, 2024 [70]; Shirani et al., 2022 [71]; Charles et al., 2025 [72]; Fowler Davis and Davies, 2025 [9]; Coyne et al., 2018 [73]; Sarmiento and Sims, 2015 [74]; Varady et al., 2015 [75]; Davis et al., 2024 [76]; Wågø et al., 2016 [77]; Camprubí et al., 2016 [78]; Fang et al., 2016 [79]; Braubach and Ferrand, 2013 [80]
Environmental Considerations	Ghisellini et al., 2016 [29]; Munaro et al., 2020 [81]; Almeida et al., 2018 [20]; Sojkova et al., 2019 [82]; Cal et al., 2021 [83]; Barbosa et al., 2022 [84]; Chandrasekaran et al., 2021 [85]; Soust-Verdaguer et al., 2023 [86]; Mer-cader-Moyano et al., 2020 [87]; Bragadin et al., 2023 [88]; Mercader-Moyano and Ramos-Martín, 2020 [7]; Cottafava and Ritzen, 2021 [89]; Chandrasekaran and Dvarionienė, 2022 [90]; Ghose et al., 2017 [91]; Schau & Prelovšek Niemelä, 2024 [92]; García-Pérez et al., 2018 [93]; Omrany et al., 2020 [94]; Pombo et al., 2016 [4]; Benedetti et al., 2025 [95]; Pittau et al., 2019 [96]; Paleari et al., 2016 [97]
Digitization and Data-Driven Systems for Climate Resilience	Sassanelli et al., 2019 [98]; Cangelli et al., 2024 [99]; Kaewunruen et al., 2024 [6]; Mazzoli et al., 2022 [100]; Klingler et al., 2025 [101]; Vergerio et al., 2018 [102]; Ca-puto and Pasetti, 2017 [103]; Fořt et al., 2022 [104]; Abram et al., 2022 [105]; Gaspari et al., 2021 [106]; D'Oca et al., 2018 [21]; Tretter, 2015 [107]; Kivimaa and Martiskainen, 2018 [108]; Tetteh et al., 2022 [109]; Sáez-de-Guinoa et al., 2022 [12]; Rahla et al., 2021 [110]; Becker et al., 2020 [111]; Pallett et al., 2019 [112]; Ness and Xing, 2017 [113]; Monzón-Chavarrías et al., 2021 [114]

3.2. Thematic Cluster Analysis

(1) **Technical Enablers (Dominant but Siloed)**

The most extensively researched cluster includes 22 studies focusing on technical enablers, including modular construction, prefabrication, smart renovation tools, and high-performance insulation materials [32,34]. While studies emphasize energy efficiency and operational carbon reductions, circular material reuse is limited [20].

Similarly, despite advances in Building Information Modeling (BIM) and lifecycle assessment tools, their application in circular renovation remains limited [65]. Furthermore, bibliometric mapping reveals a strong correlation between "energy efficiency" and "building performance", yet a weak presence of terms such as "material reuse" and "circularity", suggesting that CE principles are not yet fully embedded in technical renovation methodologies [8].

The reliance on technological advancements without system-wide policy and financial incentives creates an innovation paradox despite technical feasibility, market uptake remains low due to economic and policy fragmentation [31]. A compelling example is the Corte Palazzo pilot project in Argelato, Italy, which applied prefabricated circular renovation modules in a social housing context [100]. While the project demonstrated strong technical performance, it also highlighted that despite regulatory alignment and sustained financial incentives, innovative solutions could remain limited to isolated pilot initiatives rather than scaled or sustained.

(2) **Economic and policy barriers (Underdeveloped and Weak Connections)**

The cluster is represented by 18 studies underscoring the continued fragmentation of economic feasibility models and policy frameworks related to CE-DER implementation [30,54].

The low occurrence and weak interconnections of terms such as "financial incentives", "investment models", and "policy mechanisms" indicate a lack of structured financial pathways for CE-DER [3]. Although the EU policy documents propose mechanisms like tax incentives and green bonds, their implementation remains inconsistent, leading to investor uncertainty [84]. Similarly, regulatory fragmentation across EU nations creates uncertainty, slowing the adoption of circular renovation strategies [56].

A relevant case is Italy's Superbonus 110% scheme, which initially offered full tax rebates for deep renovations, including energy efficiency and seismic upgrades. While the policy led to a rapid increase in renovation activity, it also exposed the risks of poorly coordinated financial and regulatory systems. Sudden policy changes, budgetary constraints, and administrative bottlenecks created instability, resulting in stalled projects and market distrust [115]. This example illustrates how even the well-intentioned financial incentives can backfire without long-term policy stability, transparent eligibility criteria, and alignment with circular objectives.

(3) **Social Sustainability Factors (Marginalized in Research Priorities)**

The social dimension of CE-DER is one of the least explored areas, with stakeholder participation, energy poverty, and social inclusion largely absent from mainstream research [53,99]. This cluster includes 17 studies, reflecting a systemic underrepresentation of social equity considerations in mainstream renovation discourse. Bibliometric analysis reveals dominance of keywords such as "energy performance" and "building efficiency", over "energy poverty", "public housing", and "tenant participation" in keyword mapping suggests a research bias toward efficiency metrics over equitable renovation benefits, particularly in vulnerable communities [65,66].

The neglect of social sustainability has practical implications: without meaningful community engagement and strategies to address displacement or affordability, even well-funded CE-DER initiatives may face resistance or fail to reach those most in need. A compelling example is the Corte Palazzo project in Argelato, Italy, which incorporated tenant co-design processes in the renovation of social housing using circular prefabricated modules [100]. This approach not only improved project acceptance and satisfaction among residents but also showed how inclusive planning can reinforce both technical and social outcomes.

Overall, this cluster highlights a critical gap in mainstream CE-DER strategies of social equality resulting in the limited uptake and long-term success of renovation strategies.

(4) **Environmental Considerations (Well Represented but Poorly Integrated)**

This cluster comprises 21 studies focusing on environmental metrics such as life cycle analysis (LCA), embodied energy, and carbon emissions. The terms such as "life cycle analysis", "embodied energy", and "carbon emissions" validate that sustainability assessments are a well-established research domain.

However, the isolation of keywords like "waste reduction", "material reuse", and "circular economy" indicates that CE principles are not fully embedded into deep renovation methodologies. While life cycle assessments are frequently applied to evaluate renovation impacts, their integration into circular construction models remains weak. A key issue is the lack of EU-wide material certification policies, limiting the scalability of secondary material use [34]. This issue is particularly problematic in public procurement contexts, where strict standards often exclude recycled content by default.

A relevant example is Finland's performance-based environmental standards, promoted by innovation bodies like Sitra [116]. These standards support the use of circular materials by assessing performance outcomes rather than prescriptive inputs. This approach enables more flexible and scalable integration of circular practices while maintaining high environmental standards.

Overall, this cluster shows that while environmental assessment is mature, its operational synergy with circular renovation strategies is still underdeveloped posing both a policy and technical coordination challenge.

(5) **Digitization and Data-Driven Systems for Climate Resilience (Poorly interlinked with CE and DER)**

This cluster comprises 20 studies and focuses on the role of digitalization, smart monitoring, and data infrastructure in enhancing climate resilience within CE-DER. Keywords such as "monitoring systems", "building performance", "data-driven decision-making", and "digital tools" highlight the growing academic and policy interest in leveraging digital infrastructure to optimize renovation outcomes and support adaptive, evidence-based climate strategies [5,117].

The cluster underscores increasing recognition that digitalization can accelerate energy transitions by improving efficiency, and reinforcing the data-policy feedback loop, reducing uncertainty, and enabling operational responsiveness [118]. However, the bibliometric analysis also reveals notable limitations. Terms associated with financial governance, data privacy, and social inclusion are weakly integrated, suggesting that much of the existing literature under-theorizes the risks of technological exclusion and resistance. The weak association between terms such as "digital equity", "energy poverty", and "resilience" further indicates a persistent gap in addressing the socio-technical dimensions of digital transition planning.

The Syn.ikia project, funded under Horizon 2020, offers an example of how these challenges can be addressed. Deployed in several European contexts including Trondheim (Norway) and Lustenau (Austria) the project establishes Plus Energy Neighborhoods equipped with real-time building performance dashboards, user-centered feedback systems, and smart energy monitoring tools [119,120]. These systems support energy-behavior tracking, policy co-creation, and adaptive design, contributing directly to climate resilience. Syn.ikia demonstrates that digitalization when combined with inclusive governance and robust privacy safeguards, can transform CE-DER from a technical concept into a socially grounded and operationally viable framework.

Overall, this cluster positions digitalization as both a technical and governance challenge. It offers promising tools for climate resilience, while also highlighting the need to avoid techno-centric approaches that neglect social trust, ethical data use, and institutional adaptability.

3.3. Causal Loop Analysis of Systemic Dynamics in CE-DER

This section presents a system-level analysis of the complex, interrelated dynamics that shape the adoption and implementation of Circular Economy principles within Deep Energy Renovation (CE-DER) processes. Using Causal Loop Diagrams (CLDs), the study visualizes reinforcing and balancing feedback loops across five thematic clusters, previously identified through bibliometric and qualitative analysis. This approach enables a deeper understanding of how technical, economic, social, environmental, and digital dimensions interact to either reinforce progress or create bottlenecks in CE-DER transitions.

(1) **Technical Enablers**

The cluster captures how innovation, investment, material circularity, and policy support interact to shape the pace and stability of CE-DER adoption. These drivers do not act independently; instead, they operate through four interlinked feedback loops, two reinforcing and two balancing, that together define both the system's potential and its vulnerability (Figure 6).

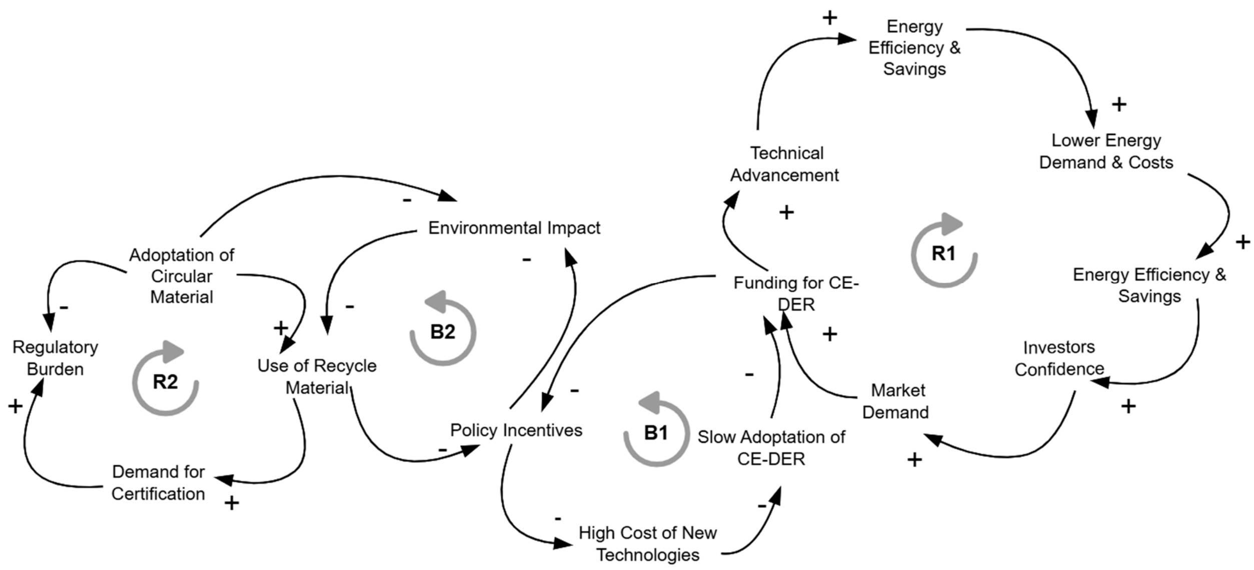

Figure 6. CLD—Cluster 1: Technical enablers: Balancing innovation, cost, and circular performance.

At the core of the system is Reinforcing Loop R1: Innovation–Efficiency–Investment, where Investor Confidence leads to increased Funding for CE-DER, enabling Technical Advancement. This advancement improves Energy Efficiency and savings, reducing Energy Demand and costs, thereby feeding back investor confidence. This loop reflects the ideal trajectory of CE-DER, where demonstrated performance continuously attracts new investments and accelerates technical improvements.

However, this momentum is checked by Balancing Loop B1: High-Cost Barrier. The high upfront costs of emerging technologies limit their adoption, suppressing market demand. As successful projects remain scarce, investor confidence declines, reducing the funding needed to scale innovation. This cycle creates a classic adoption trap, where low uptake sustains high costs, and high costs, in turn, hinder broader adoption.

Material flows introduce a second reinforcing dynamic through Loop R2: Policy Incentives and Circular Uptake. Well-designed policy incentives encourage technical innovation and the use of recycled materials, as demonstrated in parametric design application at the district level in Bologna [121]. As adoption rises, environmental impacts decrease, which in turn justifies continued or expanded policy support. This loop plays a critical role in aligning technological innovation with environmental goals, especially when circular design complements energy efficiency.

However, the Balancing Loop B2: Certification Burden constrains this potential. As the use of recycled materials grows, so does the demand for certification and compliance. These regulatory requirements increase the administrative burden, delaying project timelines and slowing adoption. This creates a bottleneck that limits the effectiveness of policy incentives, especially when certification systems lag material innovation.

These four loops form a tightly interconnected subsystem. Pressure to reduce technology costs in B1 must be addressed without intensifying regulatory constraints in B2. Meanwhile, strong policy performance in R2 can help accelerate R1 by improving material uptake and system efficiency. However, breakdowns in any single loop such as unresolved certification challenges in B2 can ripple through the system, eroding investor trust, limiting funding, and stalling innovation.

(2) **Economic and Policy Barriers**

This cluster highlights how institutional fragmentation and administrative complexity slow the implementation and scaling of CE-DER initiatives. The feedback dynamics in this subsystem reveal a persistent structural drag driven by misaligned policy frameworks, regulatory bottlenecks, and disconnected funding streams, (Figure 7).

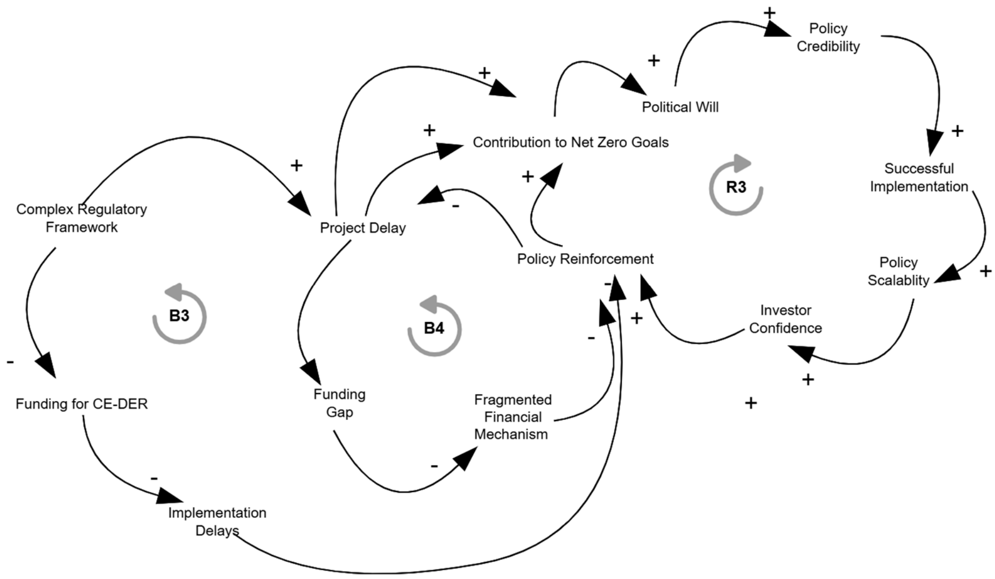

Figure 7. CLD—Cluster 2: Economic and policy barriers.

Balancing Loop B3 captures how complex regulatory frameworks introduce administrative delays. These delays weaken investor confidence, reducing funding availability and limiting project scalability. As fewer projects succeed, the pressure for policy reform diminishes, reinforcing the complexity. This loop reflects a self-reinforcing cycle of bureaucratic inertia, where weak implementation capacity perpetuates regulatory stagnation.

Overlaying this is balancing loop B4, which focuses on fragmented financial mechanisms. Misaligned funding sources, inconsistent eligibility criteria, and short-term incentives lead to funding gaps and project delays. These setbacks slow progress toward net zero targets, weakening policy reinforcement and reducing political support for integrated climate-finance strategies. As coherence in governance erodes, fragmentation deepens, completing a loop that undermines delivery even in the presence of strong climate ambitions.

However, reinforcing loop R3 begins with successful implementation which is often achieved through pilot programs or coordinated demonstration projects. These successes build policy credibility, which strengthens political will and drives policy reinforcement. In turn, better-aligned policies and delivery models improve project scalability, increasing the likelihood of further success. This loop illustrates how early wins, and institutional learning can generate upward momentum in an otherwise stagnant system.

Together, these three loops reflect a dual dynamic, B3 and B4 act as persistent structural brakes, while R3 holds the potential for institutional breakthrough. Without proactive investment in R3 through transparent performance metrics, cross-sector alignment, and scaling of demonstrable pilots the system risks remaining in a cycle of limited implementation despite strong policy aspirations.

(3) **Social Sustainability Factors**

The Social Sustainability Factors cluster captures the dynamic relationship between tenant engagement, stakeholder support, institutional trust, and social acceptance factors that significantly influence the feasibility and public legitimacy of CE-DER initiatives. This subsystem presents a mix of reinforcing and balancing feedback loops that either unlock or constrain community-driven renovation (Figure 8).

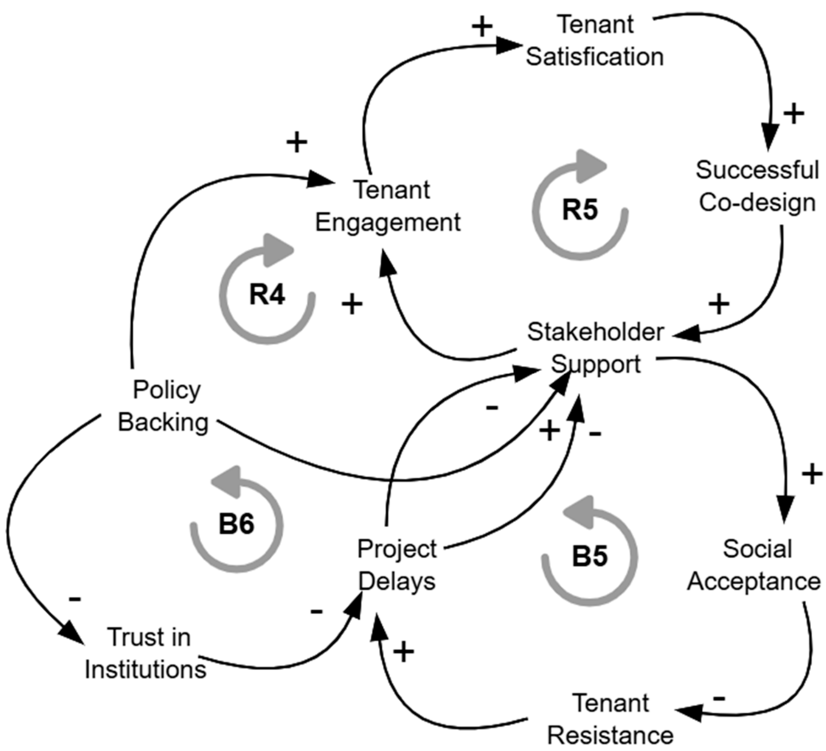

Figure 8. CLD—Cluster 3: Social sustainability factors.

At the core lies a socially driven reinforcing loop R4, where increased policy backing leads to greater tenant engagement, which in turn enhances stakeholder support. Support then feeds back into policy commitment, completing a trust-driven cycle of social momentum. This loop is crucial for demonstrating that technical or financial instruments alone are insufficient without deep engagement and perception management.

Complementing this is reinforcing loop R5, which centers on the quality of participatory design. Higher levels of tenant engagement increase the likelihood of successful co-design, leading to greater Tenant Satisfaction. This satisfaction, in turn, elevates public expectations and support for broader policy backing, thus reinforcing institutional alignment. The synergy between participatory quality and outcome legitimacy reveals how user-centered design directly drives systemic acceleration.

However, two balancing loops introduce counterforces, balancing loop B5 captures how tenant resistance which often stems from past negative experiences or inadequate communication reduces social acceptance. This limits stakeholder support, delays projects, and further increases resistance, forming a feedback loop of community disengagement and fragmentation.

Meanwhile, balancing loop B6 reveals how project delays erode trust in institutions. diminished trust weakens stakeholder support, which undermines policy backing, reinforcing further project stagnation, and contributing to institutional fatigue.

What emerges from this cluster is the systemic tension between social inertia and participatory legitimacy. Without genuine engagement and mechanisms to build trust, even well-funded initiatives risk failure. Conversely, when communities are positioned as co-creators rather than passive recipients, positive feedback loops like R4 and R5 activate, accelerating implementation while reducing perceived risks. The system map in Figure 8 thus visualizes the delicate socio-institutional interface where emotional, behavioral, and governance factors converge.

(4) **Environmental Considerations**

The Environmental Considerations cluster captures the system-level dynamics influencing circular material adoption, environmental performance, and innovation cycles in the context of CE-DER transitions. This cluster emphasizes the need to balance regulatory demands with investment momentum and performance-driven incentives (Figure 9).

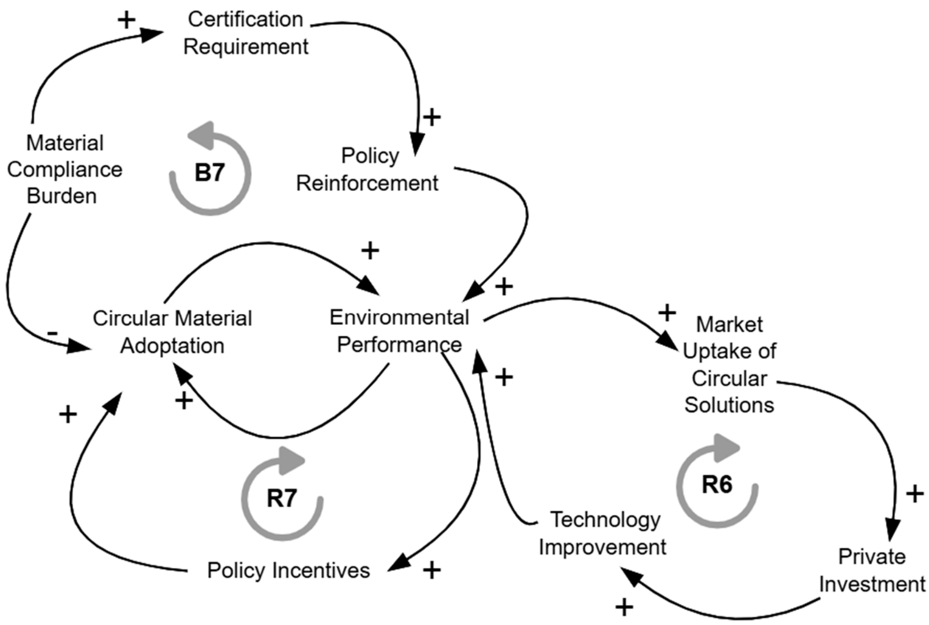

Figure 9. CLD—Cluster 4: Environmental considerations.

A key balancing feedback loop is B7, which begins with stricter certification requirements. These elevate the material compliance burden, which may slow circular material adoption. Slower uptake diminishes overall environmental performance, weakening the case for further policy reinforcement. This loop demonstrates how overly rigid compliance systems if not supported by adaptive regulatory mechanisms can hinder progress toward broader environmental goals by placing disproportionate burdens on innovation pathways.

In contrast, reinforcing loop R7 shows the role of policy incentives in accelerating sustainable material flows. Supportive policy instruments stimulate greater circular material adoption, leading to measurable gains in environmental performance. improved outcomes help validate the effectiveness of those same incentives, feeding back into continued or expanded policy momentum. This loop highlights how thoughtful incentive structures can foster system-wide improvement.

A second positive feedback mechanism, reinforcing loop R6, captures the link between environmental performance and market uptake of circular solutions. As environmental outcomes improve, private actors become more confident, increasing private investment in circular innovation. Investment boosts technology improvement further enhances performance and expands uptake. This loop emphasizes how market-based signals and long-term policy certainly are essential for mobilizing private-sector contributions to sustainability transitions.

Together, these loops articulate a critical balance between regulation and enablement. While oversight and certification are necessary to ensure environmental integrity, excessive compliance burdens captured in B7 can restrict the very momentum that R6 and R7 seek to build. The system map (Figure 9) demonstrates that effective transition pathways will require a policy posture that both guides performance and actively enables innovation, rather than constraining it through administrative rigidity.

(5) **Digitization and Data-Driven Systems for Climate Resilience**

Cluster 5 illustrates the role of digitalization and data-driven systems in shaping operational efficiency, stakeholder trust, and evidence-based policymaking in circular energy deep renovation (CE-DER) processes. The subsystem is structured around two reinforcing loops R8 and R9 and one balancing loop B8, revealing both the transformative potential and key risks of digital innovation in the built environment (Figure 10).

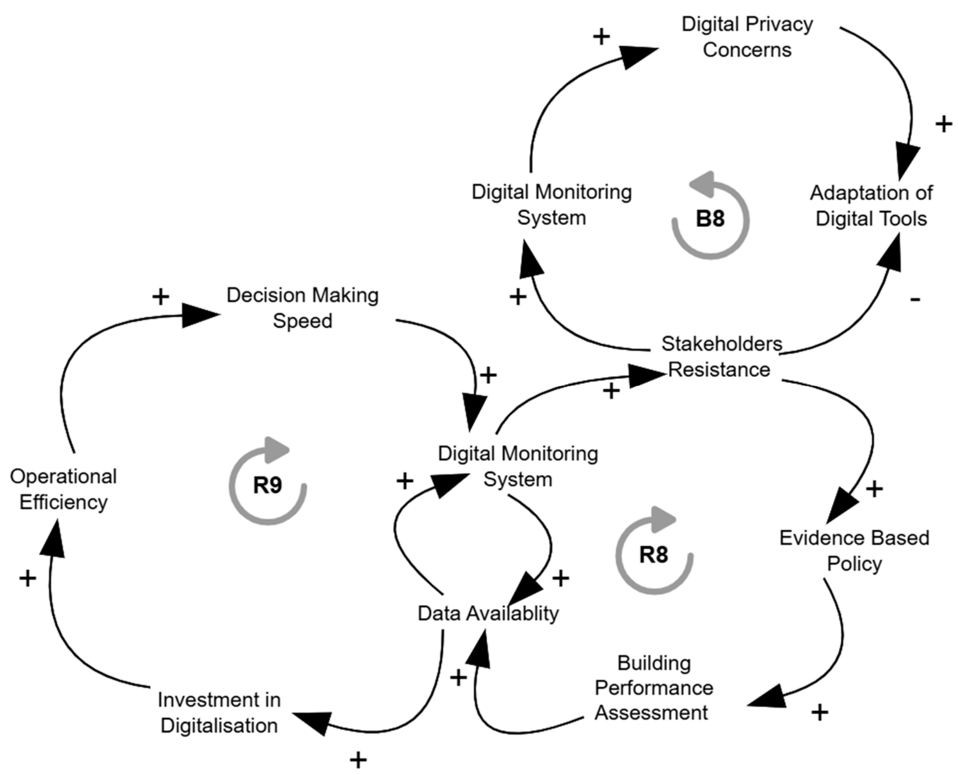

Figure 10. CLD—Cluster 5: Digitalization and data.

Reinforcing loop R8 focuses on the institutional learning cycle driven by digital monitoring systems. As monitoring tools expand, data availability improves, strengthening building performance assessments. These assessments inform the development of evidence-based policies, which in turn reinforce institutional legitimacy and support digital adoption. As policies increasingly rely on performance data, trust in monitoring technologies grows, driving broader uptake and continuous feedback [122]. This loop underscores how well-structured feedback systems support both technical precision and responsive governance.

Reinforcing loop R9 emphasizes digitalization's role in enhancing operational efficiency. Beginning with investment in digitalization, this loop boosts data availability, which increases decision-making speed and improves efficiency. The resulting performance gains justify further investment in digital tools. This loop reflects how digital maturity enhances real-time project management, accelerates interventions, and unlocks cost-effective, system-wide improvements in CE-DER programs.

In contrast, balancing loop B8 introduces a critical social constraint. As the use of digital tools expands, digital privacy concerns among stakeholders particularly building occupants also rise. These concerns can lead to stakeholder resistance, which slows the adaptation of digital tools, reducing the effectiveness of monitoring systems and disrupting feedback cycles in R8 and R9. This loop highlights that digital transitions are not purely technical; they must also address ethical, legal, and emotional dimensions of trust and consent.

Taken together, these loops reveal a complex but promising digital ecosystem. On one hand, feedback-driven learning and operational acceleration offer significant benefits for climate resilience and circular transition. On the other, poorly managed data practices risk backlash and implementation delays. As shown in Figure 10, the success of digitalization in CE-DER depends not only on technological integration but also on proactive transparency, inclusive engagement, and institutional safeguards to ensure trustworthiness and ethical compliance.

The five CLDs reveal a web of reinforcing drivers and counterbalancing constraints that govern the pace, direction, and equity of CE-DER transitions. While positive loops—such as innovation cycles R1, community co-design R4, and material reuse R7 highlight systemic potential, they are frequently constrained by structural impediments like certification burdens B2, financial fragmentation B5, and social resistance B3. These balancing dynamics reflect not only technical and regulatory barriers but also a deeper misalignment across institutional, social, and economic systems. A key insight is the presence of systemic lock-in highlighting unless policy, finance, and participation mechanisms are reconfigured in tandem, the CE-DER agenda may remain confined to isolated pilot projects. The CLDs also suggest that enabling loops are interconnected strengthening one (e.g., digital trust) may reinforce others (e.g., performance-based finance), offering potential leverage points for transformative change.

4. Discussion

4.1. Understanding Systemic Feedback: Barriers and Reinforcers

The findings highlight the complexity of implementing Circular Economy in Distributed Energy Resources (CE-DER) frameworks. This approach is characterized by the interaction of reinforcing and balancing feedback loops across technical, institutional, social, environmental, and digital domains. The causal loop diagrams (CLDs) developed in this study provide a system-level view of these interdependencies.

A persistent tension emerges between reinforcing loops (R1–R9), which can drive momentum, and balancing loops (B1–B8), which act as structural barriers that inhibit large-scale transformation. Balancing loops dominate across all clusters, helping explain why CE-DER initiatives often stall despite advanced technologies and ambitious policies [5,111]. For instance, tech cost barriers (B1), certification bottlenecks (B2), regulatory delays (B3), and financial fragmentation (B4) undermine innovation and institutional trust, despite strong technical and policy intentions. These findings align with broader concerns about implementation gridlock in energy transitions, particularly when economic and regulatory tools lack coordination [91].

Conversely, certain reinforcing loops, such as policy learning (R3), circular incentives (R2), and participatory engagement (R4, R5), illustrate conditions under which systemic momentum can be built. Closing feedback loops such as linking real-time performance monitoring to policy adaptation (R2, R6, R8) emerge as critical to enabling more adaptive and resilient renovation pathways. These insights reinforce the notion that the success of CE-DER is contingent not only on technological advancement but also on the systemic integration of institutional, social, and policy dimensions.

4.2. Policy Coherence, Social Trust, and Digital Governance

Policy fragmentation and institutional resistance are consistently revealed as major obstacles across Clusters 2, 3, and 5. While reinforcing mechanisms like successful pilot projects (R3) can strengthen policy credibility, regulatory complexity and inconsistencies—exemplified by programs such as Italy's Superbonus 110% often erode market confidence and delay uptake.

Social dynamics further complicate transactions. Resistance among stakeholder resistance (B5) and institutional fatigue (B6) do not stem from technological inadequacy but from procedural exclusion and lack of participatory governance. These patterns align with the existing research indicating that resistance to retrofit programs is often rooted in engagement deficiencies rather than technical or design-related flaws [65,72].

Digitalization, while offering significant potential to enhance evidence-based policy-making and operational efficiency (R8, R9), introduces its own set of challenges. Concerning data governance, privacy, and digital exclusion (B8) risk undermining trust and slowing digital tool adoption if not properly addressed. This underscores that digital strategies for CE-DER must be accompanied by robust ethical safeguards and inclusive practices to ensure widespread legitimacy and effectiveness. These dynamics reflect broader critiques of "digital rebound" effects and ethical oversights in data-centric governance models [118,122].

These findings indicate that the primary barriers to CE-DER implementation are institutional rather than technological or financial. Misaligned policies limit cross-sector coordination and fragile trust structures frequently hinder progress particularly when digital tools are deployed without ethical oversight or genuine stakeholder engagement. The effectiveness of digital governance depends on how well it addresses critical concerns such as consent, transparency, and accountability; without this, it risks undermining system performance rather than enhancing it. To be effective, the CE-DER transitions must combine technological innovation with governance approaches that are inclusive, coherent, and responsive to social and ethical concerns [110].

4.3. Strategic Leverage Points for a Scalable Transition

Despite the dominance of balancing loops, the CLD analysis identifies several systemic leverage points—areas where targeted interventions can unlock reinforcing dynamics and overcome institutional inertia.

Public investment and streamlined certification processes can activate innovation efficiency loop(R1) (Innovation–Efficiency) and circular uptake loop (R2), accelerating market diffusion. Furthermore, well-executed pilot projects supported by transparent performance metrics can strengthen institutional learning and credibility (R3) (Institutional Reform) and improve coordination across fragmented financial mechanisms [113,117].

The empirical relevance of this analysis is further supported by selected real-world applications. For instance, Italy's Corte Palazzo social housing pilot in Argelato explicitly demonstrates the viability of combining circular prefabrication with inclusive tenant co-design (reinforcing Loop R5). Similarly, Finland's approach to performance-based environmental certification effectively aligns regulatory mechanisms with circular economy principles, highlighting adaptive policy incentives (reinforcing Loop R7). While these examples illustrate systemic potential within specific contexts, broader empirical validation remains critical for future research. Climatic, socio-economic, and institutional differences across EU regions can significantly influence the adoption and outcomes of CE-DER strategies. Future studies should develop regionally adapted models that reflect these contextual variations.

Participatory co-design and responsible digital governance are key to shape effective CE-DER systems. Loops R4, R5, R8, and R9 illustrate how inclusive engagement and effective performance feedback can reduce resistance and foster innovation. However, these outcomes depend on safeguards for data privacy and equitable stakeholder involvement. Furthermore, the results highlight the critical role of policy design in balancing compliance mechanisms (B7) with incentives that activate market uptake (R6) and environmental performance (R7). Lifecycle-based assessment tools and adaptive policy instruments can reduce administrative burden, support innovation, and better align environmental goals with capital flows [117].

This analysis reinforces the conclusion that CE-DER transitions require multi-loop strategies coordinated efforts that activate interconnected subsystems rather than isolated interventions. Scalable progress depends on adaptive, ethically grounded approaches integrating technical, institutional, and social dimensions of transformation [112,123]. Table 4 summarizes these most influential feedback loops and the corresponding strategic actions across clusters.

Table 4. Cross-cluster feedback loops and strategic leverage points.

Cluster	Key Reinforcing Loops (R)	Key Balancing Loops (B)	Leverage Point or Insight
Cluster 1—Technical Enablers	R1: Innovation–Efficiency–Investment R2: Circular Incentives and Uptake	B1: Tech Cost Barrier B2: Certification Bottleneck	Aggregate public investment to reduce tech cost and reform certification standards.
Cluster 2—Economic and Policy Barriers	R3: Policy Learning and Institutional Reform	B3: Regulatory Delay B4: Financial Fragmentation	Use pilot success to strengthen policy credibility and integrate fragmented finance.
Cluster 3—Social Sustainability Factors	R4: Policy Trust and Support R5: Co-Design and Satisfaction	B5: Resistance from Past Experience B6: Institutional Trust Erosion	Support co-design and early engagement to prevent resistance and delays
Cluster 4—Environmental Considerations	R6: Market Uptake and Private Investment R7: Circular Incentive Effectiveness	B7: Certification and Material Compliance Burden	Balance compliance with incentives to boost environmental outcomes and innovation
Cluster 5—Digitalization and Data-Driven Systems for Climate Resilience	R8: Evidence-Based Policy Feedback R9: Operational Efficiency Gains	B8: Privacy Concern and Stakeholder Resistance	Build trust through transparent data governance and adaptive digital tools.

4.4. Limitations of the Research

While this study offers a comprehensive system-level analysis of CE-DER dynamics, it has some limitations. First, the analysis is grounded in the European Union's policy and regulatory context, which may limit the direct applicability of insights to regions with different socio-economic and institutional conditions. Second, although the systematic review followed PRISMA guidelines and relied on robust database selection (Scopus and Web of Science), the literature analyzed remains constrained by the evolving terminology within the CE and DER research fields. Third, the causal loop diagrams (CLDs) developed in this study are conceptual models synthesized from secondary sources; their validity would be strengthened through empirical testing and participatory stakeholder engagement. To address these limitations, a forthcoming research activity will integrate empirical stakeholder inputs and evaluate the effectiveness of identified leverage points through case studies and field-based modeling.

5. Conclusions

This study applied a systems thinking approach to examine the feedback dynamics shaping the implementation of circular economy-based deep energy renovation (CE-DER). It systematically reviews 99 peer-reviewed articles and classifies them into five core clusters to model key systemic dynamics. Through the structured literature review and the development of five cluster-specific causal loop diagrams (CLDs), the study maps the interactions among technical, financial, social, environmental, and digital factors, highlighting how these elements connect through reinforcing and balancing feedback loops.

The analysis reveals a persistent tension between innovation and systemic inertia. While reinforcing loops (e.g., R1, R3, R6, R8) highlight pathways to momentum—driven by investment, participation, or digital infrastructure these gains are often counteracted by entrenched balancing loops (e.g., B1, B4, B6, B8), which expose underlying policy, institutional, and behavioral constraints. Crucially, the CLDs underscore that no single factor operates in isolation; the effectiveness of CE-DER efforts hinges on coordinated interaction across multiple loops and domains.

Three key insights emerge. First, technical solutions alone are inadequate. Innovation loops stall without alignment between policy incentives, certification processes, and financial mechanisms. Second, trust and participation are essential. Whether in the context of social co-design or digital governance, stakeholder engagement determines whether reinforcing loops are activated or neutralized. Third, while digitalization offers new tools for performance and oversight, it also introduces new constraints related to privacy, legitimacy, and institutional preparedness.

From a policy standpoint, the findings point to the need for adaptive, multi-loop strategies. These include lifecycle-oriented financial instruments, performance-based incentives, and ethically designed and transparently governed digital tools. Strategic investments must extend beyond technologies to include the governance capacities that enable social, institutional, and technical systems to reinforce one another.

Finally, this study demonstrates the value of causal loop diagramming for navigating complex policy landscapes. Unlike linear cause-effect models, CLDs allow researchers and practitioners to visualize feedback-rich environments and design interventions that respond to systemic dynamics.

In conclusion, the transition to circular and energy-efficient renovation is not simply a technological challenge, it is a systems challenge. Progress will depend not only on innovative solutions but also on the capacity to design, align, and govern interconnected feedback systems.

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Abbreviations

The following abbreviations are used in this manuscript:

CE	Circular Economy
CLD	Causal Loop Diagram
DER	Deep Energy Renovation
EU	European Union

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