CHEMICAL AND MATERIAL STRATEGIES FOR ENERGY-POSITIVE BUILDINGS: A SUSTAINABILITY-ORIENTED REVIEW

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Abstract

The pursuit of a promising way to reduce the impact of energy-positive buildings on the built environment is defined as reduced energy consumption. On the other hand, sustainability cannot be based solely on operational energy performance, as it is significantly influenced by material-related factors. This study is a comprehensive review of the chemical and material foundations of energy-positive buildings and a compilation of the long-term performance of material properties and degradation mechanisms. Data synthesis and literature selection were carried out using the PRISMA method. In light of the information obtained, parameters related to energy-intensive production, material stability, and life cycle impacts were addressed by considering key material groups, including cement-based systems, polymers, and bio-based materials. The findings show that degradation processes and limited circularity remain critical challenges. Therefore, achieving sustainable energy-positive buildings requires an integrated approach that simultaneously considers material chemistry, energy system performance, and life cycle assessment.

Keywords: Energy-positive buildings, Embodied carbon, Material chemistry, Building materials.

JEL Classification: Q01, Q42, Q56, Q55

Citation: Gul Ç. G., 2026. “Chemical and material strategies for energy-positive buildings: a sustainability-oriented review”, Sustainable Regional Development Scientific Journal, Vol III. (1), pp.12-36

1. Introduction

Energy-positive buildings, that produce more energy than they consume, are key solution for sustainable construction. When buildings become more energy efficient, operational emissions decrease with embodied carbon emissions from material production, construction, and end-of-life stages can dominate the total footprint. Cement, steel, and polymer-based materials are major contributors. Therefore, material chemistry plays a critical role in this problem. Material properties define thermal behavior, durability, and environmental interactions with the parameters such as thermal conductivity, heat capacity, and chemical stability. At the same time, degradation processes with influence maintenance needs, service life, and total emissions can change material properties.

On the other hand, advanced materials have both opportunities and risks: polymer-based insulation, bio-based materials, and phase change materials improve energy performance; but, they also raise concerns about toxicity, durability, and end-of-life management. In practice, recycling, reuse, and design approaches have serious limitations such as material heterogeneity, contamination, and degradation. As a result, theoretical recycle is often not achieved in real systems.

This review examines energy-positive buildings through the view of material chemistry. The aim of the study is to connect molecular design, material performance, and system-level outcomes. With this point of view, the study provides a clearer understanding of how buildings perform over their full lifecycle with a realistic pathway. It also highlights that true sustainability requires more than energy positivity.

2. Methodological Framework

The methodological framework of this review is designed to connect what is known about energy-positive buildings, the chemical foundations of sustainability, and the tools required to assess them. It pre-planning the integration of literature selection, data synthesis, and normalization (Caldeira et al. 2024). With this integration, the framework supports cross-disciplinary synthesis that aggregates insights from energy systems analysis, green and sustainable chemistry, and life cycle assessment to yield a view of how chemical design, material choices, and building energy performance interact throughout a building's life cycle (Blinova et al. 2023).

2.1. Literature Search and Selection Strategy

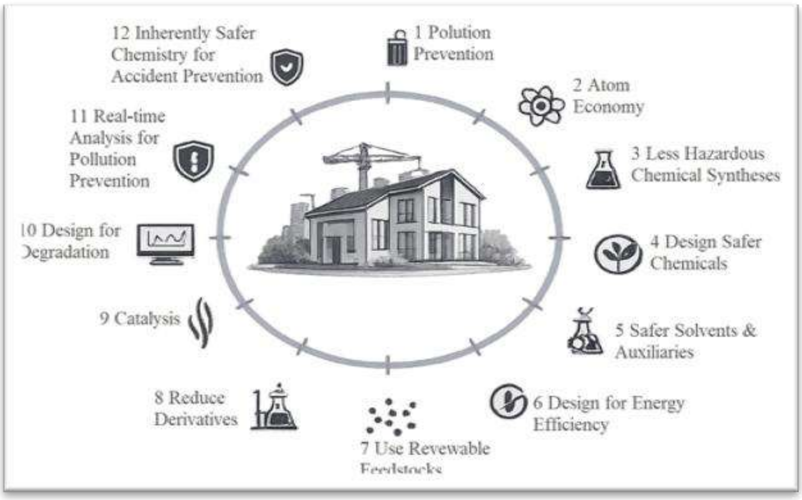
This review follows a PRISMA-inspired strategy to ensure transparent and reproducible study for the topic "Energy-Positive Buildings and the Chemical Foundations of Sustainability". I defined a comprehensive search protocol within two major databases, Scopus and Web of Science. This approach is consistent with PRISMA principles of explicit reporting of search strategies, database sources, and search terms as decribed in the literature (Soloveichik 2011).

3. Chemical Foundations of Energy-Positive Buildings

3.1. Green Chemistry in the Built Environment

Green chemistry (fig.1) provides a chemical foundations looks for rethinking construction materials and building systems over operational energy, guiding material choices, processing, and end-of-life pathways toward lower embodied harm. Key principles such as waste prevention, safer chemicals, energy efficiency, and the use of renewable feedstocks reform into the built environment emphasize designing systems that minimize waste and emissions at the cradle-to-grave scale, curtail toxic exposures, and reduce demand for virgin resources. In practice, this translates to formulating binders and coatings with lower embodied energy and toxicity. These employing processes that avoid waste streams, and prioritizing materials whose production, use, and disposal enact a net environmental benefit when evaluated across the life cycle (Goh and Ng 2016).

Figure 1. Twelve Principles of Green Chemistry to construction materials



Material chemistry shapes sustainability when operational energy is controlled. Embodied carbon, toxicity, and resource efficiency arise as material-level constraints. As a critical view, despite promising life-cycle analyses, the adoption of new chemicals is tempered by durability and compatibility (Vijayan et al. 2023). Overall, green chemistry offers a route to decarbonize the built environment, but its realization depends on material innovations with lifecycle performance, safety, and systemic integration within the construction sector (Booth and Jankovic 2022).

3.2. Material Safety, Toxicity and Indoor Chemistry

Building materials are active determinants of indoor chemical environments, leading to the sustained release of volatile organic compounds (VOCs) and semi-volatile organic compounds (SVOCs), gas emissions from adhesives and resins, and secondary chemical reactions (Coffaro and Weisel 2022). While low-emission materials and source-control strategies can reduce primary VOC loads, there remains substantial uncertainty about long-term exposure to a broad, evolving mix of emissions and reaction products. Reviews emphasize that while reducing VOC emissions and employing materials with documented low emissions is beneficial, it does not automatically translate to safer indoor environmentsThis reality reveals that material selection must be shaped by consideration of indoor air quality guidelines, adequate ventilation design, and indoor chemical reactivity in order to achieve truly energy-positive results (C. W. Yu and Kim 2012).

3.3. Carbon Intensity of Material Production

Carbon intensity in construction materials (fig.2) is the mass of greenhouse gases emitted per unit of material or area, commonly expressed as kg CO_2-eq per kg of material over the material's life cycle. This metric captures embodied emissions from material production, processing, and delivery, distinct from operational energy performance during the building's use phase (Lobaccaro et al. 2018). In many building materials, embodied carbon is determined by the material product stages (A1-A3), which generally account for the largest share due to cement and steel-based systems, clinker production, high-temperature processing, and complex supply chains (Nath et al. 2018a). Hybrid and process-based life cycle analyses reveal significant differences in embodied carbon between materials and regions, depending on factors such as energy tariffs, upstream frontier selections, and data completeness. Nevertheless, cement, concrete, and steel consistently stand out as the primary carbon sources when comparing typical high-rise and solid wood structures (Wan Mohd Sabki Wan Omar et al. 2014). These patterns underscore the importance of up-front material choices in carbon accounting, even when a building achieves low operational energy.

Figure 2. Representative proportional contribution of primary construction materials to embodied carbon in building assemblies.

3.4. Distinctions and Material Comparisons

Efficient envelopes or systems reduce operating emissions, but materials with high embodied carbon may dominate lifecycle emissions, particularly if operational energy reductions are modest or offset by long lifespans and end-of-life dynamics. Several studies show that low-energy buildings can still accrue high lifecycle emissions if embodied intensities are high or if biogenic or recycled content is not effectively accounted for; thus the overall carbon performance hinges on material selection as much as on efficiency measures during use (Lausselet et al. 2019; Nordby and Shea 2013). Representative cradle-to-gate embodied CO_2 ranges for conventional mineral-based materials and selected recyclable or composite alternatives are summarised in Table 1. These indicative ranges illustrate that carbon intensity is strongly pathway-dependent and cannot be interpreted independently of processing temperature, feedstock origin, and recyclability potential. When comparing material categories, mineral-based systems generally exhibit higher carbon content per unit area than wood-based or bio-based alternatives. However, advancements in low-clinker cements, recycled steel, and cross-laminated timber may shift this balance. Mass timber designs often act as biogenic carbon sinks and can achieve positive lifecycle footprints, particularly when considering carbon absorbed during growth and carbon sequestration at the end of its life cycle (Chen et al. 2020; Felmer et al. 2022). The literature consistently warns that it is incorrect to assume that any single material category guarantees low life-cycle emissions, and a holistic assessment including A1-A5 and beyond, potential biogenic storage, and end-of-life pathways is required for robust comparisons (Lausselet et al. 2019).

Table 1. Indicative Embodied CO2 Ranges for Conventional and Recyclable/Composite Construction Materials

Material Category	**Indicator (Typical Basis)**	**Embodied CO2 Range (kg CO2e / kg)**	**Notes**
Concrete (normal strength, mix-dependent)	Mass-based	~0.07 – 0.15	Strongly dependent on cement content, SCM substitution, and regional energy mix (Hammond et al. 2011).
Structural steel	Mass-based	~1.3 – 2.5	Sensitive to recycled scrap ratio and electricity carbon intensity (Hammond et al. 2011).

Material Category	**Indicator (Typical Basis)**	**Embodied CO2 Range (kg CO2e / kg)**	**Notes**
Aluminum (primary-dominant production)	Mass-based	~8 – 16	Primary smelting is highly energy-intensive; recycled content reduces intensity (Hammond et al. 2011).
GFRP (glass fiber–reinforced polymer composites)	Mass-based	~1.8 – 4.6	Varies with resin system, fiber fraction, and manufacturing route (Alrehaili et al. 2025).
CFRP composite (virgin carbon fiber)	Mass-based	~50 – 60	Carbon fiber production is energy-intensive; values depend on precursor and curing method (Ramachandran et al. 2023).
Recycled carbon fiber (rCF)	Mass-based	~20 – 25	Dependent on recovery technology; significant reduction compared to virgin CF (Urruzola et al. 2025).
Engineered timber (biogenic carbon accounted)	Sequestration-adjusted	~−1.6 kg CO_2e/kg (biogenic storage basis)	Biogenic accounting depends on system boundaries and end-of-life assumptions (Orr et al. 2020).

3.5. From Molecular Design to System-Level Sustainability

With current advancements in molecular-scale design, performance criteria are being defined in classical building structures. By optimizing chemical composition, molecular architecture, and reactive pathways, scientists are able to shape properties such as ion transport, interface stability, and thermal behavior, which determine energy consumption, durability, and safety in buildings (Sharma et al. 2025). The integration of AI-assisted design and preliminary chemistry enables multi-scale mapping, from structure-property-performance relationships to system-level outcomes, and reveals how molecular-level metrics can translate into various gains in terms of energy efficiency and durability (Vu et al. 2025).

Creating energy-positive buildings of the targeted scale requires integrating materials science with building energy system design, which can only be achieved through the simultaneous optimization of building facade materials, heat storage, and active/passive HVAC strategies (Lee et al. 2025).

4. Carbon Footprint and Life Cycle Assessment

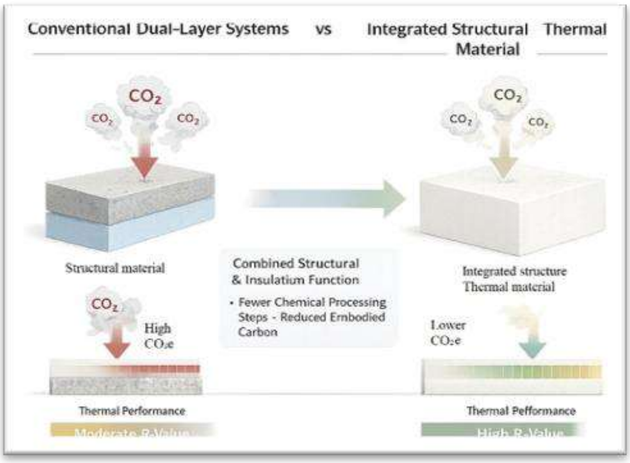
4.1. Cement and Mineral-Based Materials

Cement and mineral-based materials are central to the embodied carbon of buildings, because cementitious binders underpin the vast majority of concrete and precast elements that constitute most structures. The high-temperature clinker production step, and specifically limestone calcination, is the dominant source of process emissions in cement manufacture, while energy use for pyroprocessing contributes a substantial portion of lifecycle emissions (Reis et al. 2021). The combination of calcination-derived CO_2 release (the chemical part) and fossil-fuel combustion for kiln heat underpins why cement-based materials are frequently identified as hard-to-abate sectors in built environment decarbonization pathways (Reis et al. 2021). Beyond clinker production, the cement-to-concrete chain also modulates emissions through the clinker-to-cement ratio and the parceling of supplementary cementitious materials (SCMs), which reduce reliance on Portland cement and thereby lower the process- and energy-related footprints of the binder system (Scrivener et al. 2018). These dynamics are echoed in cross-cutting analyses of demand- and supply-side decarbonization, where SCMs, alternative binders, and carbonation concepts are foregrounded as practical levers for near-term mitigation (Pamenter and Myers 2021; Watari et al. 2022). Overall, the literature emphasizes that decarbonization is not the result of a single technology, but rather a portfolio of interdependent actions, each of which has significant impacts on structural performance, lifecycle resilience, and the ability to be implemented on a large scale across various markets (Arvizu-Montes et al. 2025).

4.2. Polymers in Insulation and Coatings

Polymer-based materials, with their superior thermal insulation and durable protective coating properties, are among the fundamental research areas of our time for reducing operating energy in buildings. In insulation, polymer foams and aerogels, generally derived from fossil-based polyols and isocyanates or alternative bio-based monomers, are used, which have low thermal conductivity (Dove et al. 2019). Throughout the life cycle (Figure 3), the need arises to evaluate the energy-performance advantages of polymers in an integrated manner with material selection, considering how various materials affect both operational energy use and the energy contained within the building cladding system (Iwuanyanwu et al. 2024).

Figure 3. Conceptual comparison between conventional dual-layer envelope systems and integrated structural–thermal materials.



Therefore, a needs assessment requires striking a balance between higher energy performance and environmental and health impacts. This encourages research into bio-based polymers and low-toxicity formulations that improve both insulation performance and lifecycle sustainability. Some of the emerging alternatives, such as bio-based binders, natural fibers, and closed-loop design concepts, show promise in terms of reducing carbon footprint while maintaining hygrothermal performance (Nasr et al. 2023; Raja et al. 2023). In this context, the development of bio-based insulation materials and low-toxicity coatings is consistent with the logic of circular building; however, careful life cycle assessment is required to ensure that their use, operation, and tangible benefits are realized throughout the process (Marín-Calvo et al. 2023).

4.3. Bio-Based Materials: Limits and Trade-offs

The construction industry is turning to bio-based materials due to limited fossil fuels, potential carbon sequestration, and regulations aimed at reducing energy consumption in building structures. However, the literature emphasizes that bio-based materials do not necessarily have entirely low-carbon or sustainable performance. Environmental benefits can be determined depending on the life cycle context, end-of-life options, and the durability of the materials during use. In conclusion, bio-based materials do not guarantee a lower carbon footprint or better life cycle performance. To achieve the targeted sustainability, their standardization should be supported through integrated design choices, protective surface treatments, and compatible matrices (Maraveas 2020).

4.4. Strengths and Limitations of LCA Methods

Life cycle assessment (LCA) is a holistic approach to evaluating the environmental performance of buildings throughout their entire life cycle (Cai et al. 2021). In the context of energy-positive buildings, Life Cycle Analysis (LCA) enables direct comparison of materials and systems, leading to lower-carbon configurations (Cabeza et al. 2021; Cai et al. 2021; Ramakrishna et al. 2021). However, LCA results are highly sensitive to methodological preferences and information gaps, and can significantly shape conclusions about a building's sustainability performance (Andersen et al. 2021). The main limitations include variability in system boundaries (A1–A5, B, C, D scopes) and allocation rules, which can lead to different energy and carbon emission outcomes for similar designs (Kayan et al. 2016). Table 2 provides a comparative qualitative assessment of integrated structural-thermal systems in terms of carbon sensitivity, recyclability, and service life durability risk.

Table 2. Comparative Qualitative Assessment of Integrated Structural–Thermal Systems Including Durability Risk

System Type	**Structural Capacity**	**Thermal Conductivity Potential**	**Recyclability Potential**	**Embodied Carbon Sensitivity**	**Service-Life Durability Risk**
Autoclaved Aerated Concrete (AAC)	Moderate	Moderate	Limited	High (cement chemistry dependent)	Moderate (moisture sensitivity, carbonation) (Ramamurthy et al. 2009)
Foamed Geopolymer Systems	Moderate (research-stage structural grades)	Moderate–Good	Moderate	Medium–High (activation route dependent)	Moderate–High (long-term durability still under study) (Tolun 2022)
Insulated Concrete Forms (ICF)	High	Good	Low	High (dual production pathways)	Moderate (polymer aging + concrete cracking) (Aci 2001)
Structural Insulated Panels (SIPs)	High	Good	Low–Moderate	Medium–High	Moderate–High (adhesive degradation, moisture ingress) (Straube and Burnett 2005)

System Type	Structural Capacity	Thermal Conductivity Potential	Recyclability Potential	Embodied Carbon Sensitivity	Service-Life Durability Risk
VIP-based Composite Panels	Low–Moderate	Very High	Low	Medium–High (processing energy sensitive)	High (vacuum loss, puncture sensitivity) (Simmler et al. 2005)
Thermoplastic Composite Sandwich Systems	Moderate–High	Good	High (mechanically separable)	Medium (electricity/fibre dependent)	Moderate (creep, UV sensitivity; matrix dependent) (Real 2023)

5. Energy Systems and Thermochemical Integration

5.1. Photovoltaic Materials and Degradation

Photovoltaic materials are a cornerstone of energy-positive buildings, enabling on-site electricity generation and complementing high-performance building facades and demand reduction strategies. In building-integrated approaches, photovoltaics (PV) play a dual role: firstly, providing clean electrical energy to meet part or all of the building's load; and secondly, enabling architectural strategies that reduce cooling and heating demands through shading and daylight interactions. In this context, bi-sided, translucent, and PV-thermal configurations have various advantages and disadvantages depending on the climate, orientation, and building use (Bošnjaković et al. 2023; Kong et al. 2023).

Degradation and aging mechanisms are of critical importance in achieving long-term performance and lifecycle energy targets. In all photovoltaic technologies, degradation results from thermal stress, prolonged UV exposure, moisture ingress, and mechanical and/or environmental aging (Maghrabie et al. 2021). In summary, the literature consistently demonstrates that uncertainty regarding the breakdown of photovoltaic technologies and installation strategies has a significant impact on achievable long-term energy efficiency (Reddy et al. 2024).

5.2. Thermal Energy Storage (PCM Systems)

Phase change materials (PCMs) enable latent heat storage in building facades and mechanical systems by absorbing or releasing large amounts of energy at nearly constant temperatures during phase transitions, thus stabilizing indoor temperatures and reducing high heating and cooling loads (Huang et al. 2021). Comparative studies show that organic phase change materials (paraffins, fatty acids) offer favorable chemical stability, non-corrosiveness, negligible phase separation, and minimal supercooling, but are inherently limited by low thermal conductivity and, in some cases, flammability. On the other hand, inorganic phase change materials (salt hydrates, hydrated salts) provide higher internal heat densities and better conductivity, but have disadvantages such as phase separation and supercooling (Huang et al. 2021). Eutectic phase change material (PCM) systems, including organic-organic, inorganic-inorganic, or organic-inorganic mixtures, can often be specifically designed to achieve target melting points and overcome some of these drawbacks; however, they also have various stabilization problems (Zhang et al. 2018).

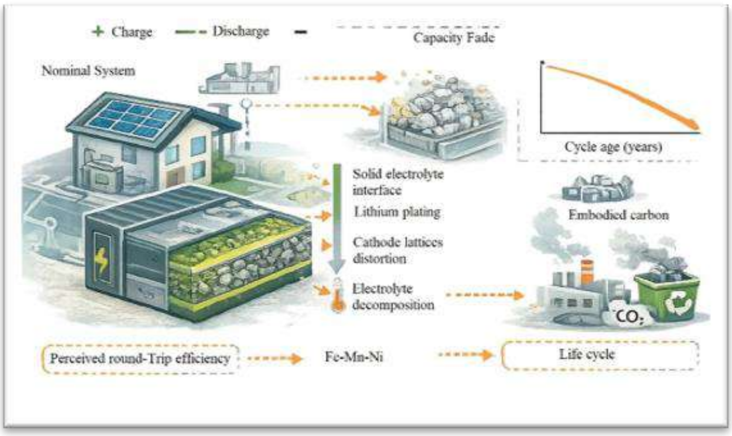
Overall, the literature on PCM systems agrees on a consistent view: while they provide significant reductions in heating and cooling loads when designed as stabilized composites with improved conductivity, various formulations can be developed considering phase stability, leakage problems, and life cycle effects in material selection. This offers promising new options for reliable and scalable building thermal energy storage solutions

(Wang et al. 2017).

5.3. Electrochemical Storage Systems

Electrochemical energy storage (ESS) systems play a central role in transforming energy-positive buildings from mere ideal concepts into practical and resilient infrastructures. Numerous studies have shown that ESS-equipped buildings enhance renewable energy integration, enable load shifting, and reduce grid emissions and stabilize on-site power profiles by increasing self-consumption (Jones et al. 2019). From an application perspective, round-trip efficiency, charge status management, and appropriately sized storage capacity determine the degree to which energy is converted into usable energy for daily operations in on-site production. Simultaneously, lifecycle considerations shape whether a storage investment will deliver net carbon and cost benefits over time (Gao et al. 2023). As shown in Figure 4, electrochemical storage systems exhibit time-dependent degradation mechanisms that directly affect the long-term energy balance of buildings.

Figure 4. Degradation pathways in building-integrated lithium-ion storage and their influence on long-term capacity and lifecycle emissions.



Sustainability considerations at the material level are of undeniable importance for long-term building performance. Critical raw materials, electrolyte formulations, and degradation pathways shape not only environmental footprints but also safety and maintenance requirements within building contexts. End-of-life management and recycling emerge as crucial levers for closing material cycles. Recent research strongly underscores the need for harmonized lifecycle analyses, standardized functional units, and open data to obtain reliable benchmarks and policy-relevant conclusions for building applications (Titirici et al. 2024).

5.4. Hydrogen-Integrated Building Systems

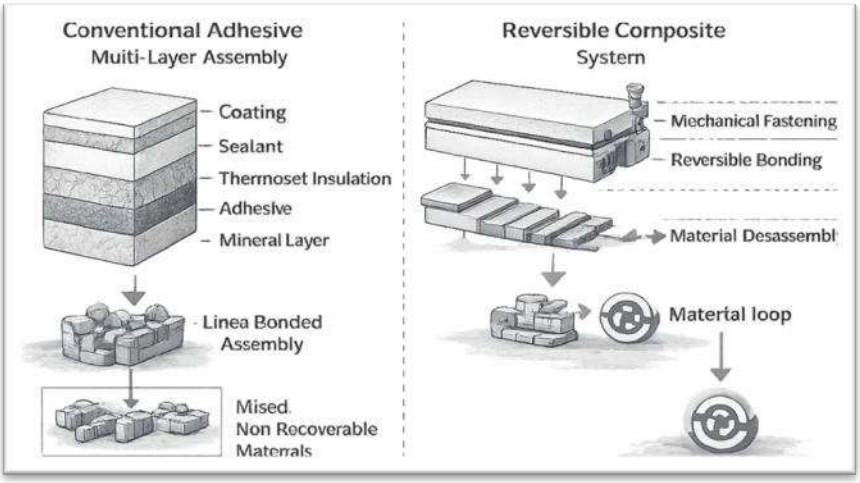
Hydrogen is increasingly being explored as a cross-sector unifying element for energy-positive buildings and a long-term energy storage medium, offering a pathway to deeper decarbonization beyond direct electrification (Cheekatamarla 2024). In this context, buildings can host a small- to medium-scale hydrogen energy system that couples electricity, heating, and potentially mobility. Oppositely, literature reports a spectrum of limitations and uncertainties. Efficiency losses arise from electrolysis, hydrogen compression, storage, and then conversion back through fuel cells or hydrogen turbines, which reduces round-trip efficiency relative to direct electricity storage technologies (Cheekatamarla 2024). Overall, studies show that while hydrogen remains an attractive option, the literature consistently highlights the need to develop infrastructure, policies, and technologies to overcome current limitations on its widespread adoption in energy-positive configurations at the building scale (Kirk 2022).

6. Material Durability and Performance Gap

6.1. Chemical Ageing Mechanisms

Extensive studies have shown that chemical aging in building materials results from fundamental processes such as oxidation, hydrolysis, carbonation, and polymer degradation. Mineral-based materials (e.g., cementitious matrices, geopolymers, and natural clays) primarily age through various pathways such as hydration/dehydration dynamics, dissolution-precipitation equilibria, and silica-alumina polymerization in response to moisture, temperature, and aggressive species (Thissen et al. 2024). Fig. 5 illustrates how bonding chemistry governs dismantlability of conventional adhesive and reversible composite. Conventional multi-layer assemblies rely on irreversible cross-linking and heterogeneous interfaces that prevent selective separation. In contrast, composite systems designed with thermoplastic matrices or reversible bonding mechanisms enable material recovery with lower thermodynamic input.

Figure 5. Conceptual comparison of conventional bonded multi-layer envelope systems and chemically reversible composite assemblies illustrating their implications for end-of-life recoverability



6.2. <u>Moisture-Induced Degradation</u>

Moisture moves through building materials via absorption, diffusion, and capillary action. In mineral-based systems, capillary rise and diffusion lead to slower transport through gels and microstructural pores. This dual system governs the timing and extent of moisture-induced chemical changes and salt transport in concrete and stone. In polymer-based matrices, moisture can soften polymers, alter free volume, and accelerate damage by facilitating diffusion across interfaces. In composites, moisture is due to interface quality and the presence of hygroscopic fillers or natural fibers. Bio-based materials increase moisture sensitivity due to the natural hygroscopicity of lignocellulose components. Thus, moisture absorption not only swells the fibers but also increases micropore transport towards the matrix, accelerating hydrolysis and biodegradation. Moisture transport, which links deterioration due to humidity to durability and indoor air quality, affects not only structural integrity but also the health of building occupants. Increased absorption and delayed drying raise indoor humidity, promote microbial growth, and affect pollutant transport, impacting energy performance and the sustainability of energy-positive buildings (Akarken et al. 2025).

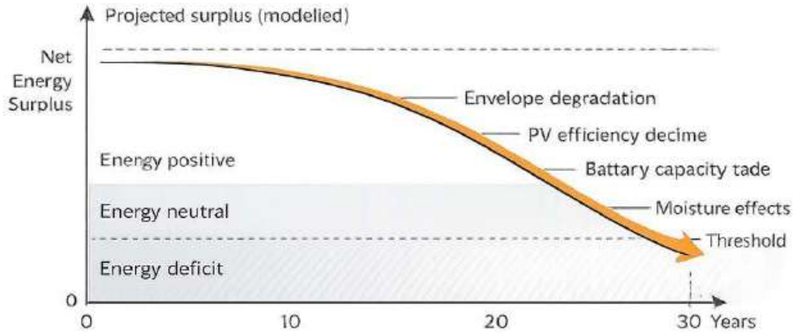
6.3. <u>Photodegradation Processes</u>

Building exterior materials are exposed to sunlight, triggering photochemical reactions initiated by UV photons absorbed by various types of chromophores. In polymeric systems, photostimulation produces radical processes manifesting as chain breaking, cross-linking, and oxidation of carbonyl groups, leading to optical discoloration accompanied by brittleness and surface cracking. These changes are associated with decreased mechanical performance and deterioration of aesthetics (Wolf 2008). In photovoltaic (PV) materials, encapsulation and barrier layers can prevent photodegradation by limiting oxygen and moisture access. However, photoinduced oxidation of active layers and interfacial degradation remain the dominant loss mechanisms. These can be most effectively mitigated through targeted encapsulation strategies rather than simply making changes to the material itself (D. Kim et al. 2024).

6.4. Long-Term Stability of Advanced Materials

Material stability is a crucial constraint in the real-world performance of energy-positive buildings, as laboratory measurements often overestimate durability after materials have been subjected to all environmental stressors encountered during service. A consistent synthesis across polymeric composites, coatings, and nanostructured systems demonstrates that long-term stability arises from the interplay of chemical aging, moisture transport, and photodegradation (Andrady et al. 2023). In fiber-reinforced and nano-enhanced coatings, the presence of UV and moisture accelerates interfacial debonding, nanoparticle migration, and matrix cracking, suggesting that long-term reliability hinges on robust interfacial adhesion and well-designed UV stabilization strategies that persist under damp-heat cycling (Jacobs et al. 2016). Moreover, the literature on self-healing and nanocomposite coatings indicates a trade-off: while embedded nanomaterials and adaptive coatings can impede early-stage degradation and offer self-repair, they can also introduce new pathways for nanoparticle release or altered aging kinetics under sustained weathering, necessitating comprehensive life-cycle risk assessments (Jacobs et al. 2016). As conceptually illustrated in Fig. 6, projected energy surplus may gradually decline as degradation mechanisms accumulate across envelope materials, photovoltaic systems, and electrochemical storage. Energy-positive status is therefore a time-dependent condition rather than a fixed design attribute.

Figure 6. Conceptual representation of time-dependent reduction in projected energy-positive margin due to material degradation, PV efficiency decline, and storage capacity fade.



Across material classes, discrepancies between short-term lab performance and field durability are pronounced and attributed to the complexity of real climates and multi-factor aging. Laboratory tests that isolate a single stressor (e.g., UV or humidity) can misrepresent long-term trajectories where synergistic interactions (photodegradation coupled with moisture ingress, thermal cycling, and environmental pollutants) govern degradation rates. For example, photostabilizers and nanocoatings can dampen visible property loss in laboratory protocols but may still fail to maintain performance under realistic UV–moisture cycling or salt-rich atmospheres, leading to unforeseen maintenance demands and higher lifecycle carbon footprints (Andrady et al. 2023). The durability of high-performance polymers and hybrid systems is thus highly contingent on the balance between intrinsic material resilience and extrinsic exposure conditions, with implications for maintenance frequency, embodied energy, and retrofit timing in energy-positive building envelopes (Berdahl et al. 2008). This synthesis underscores that achieving durable, low-carbon buildings requires explicitly accounting for long-term stability in material selection, accelerated aging interpretation, and regulatory frameworks that align short-term lab results with decades-long service expectations (Rana et al. 2025).

7. Circularity and End-of-Life Chemistry

7.1. Polymer Recycling Challenges

Recent literature across mechanical and chemical recycling of polymer-based construction materials—including insulation, coatings, and fiber-reinforced composites—highlights a persistent gap between theoretical recyclability and real-world circularity. A central theme is material heterogeneity: multilayer films, composites, and blended insulation systems comprise incompatible polymers, additives, and interfacial layers that frustrate straightforward recycling recipes (Adam et al. 2025). Even when individual components are, in principle, recyclable, the presence of tie layers, fillers, inks, adhesives, and moisture residues compromises recyclate purity and mechanical performance, limiting end-use options and often relegating streams to downcycling rather than closed-loop reuse (Adam et al. 2025). In construction waste, the same challenge manifests in insulation composites and protective coatings where diverse resin matrices and reinforcing fibers co-exist, generating immiscible blends that deteriorate as-recycled material properties and hinder uniform processing in subsequent manufacturing cycles (Peti et al. 2025).

Comparative assessment of mechanical versus chemical recycling reveals complementary strengths but also critical limitations in practice. Mechanical recycling is energy-efficient and capital-friendly but suffers progressive polymer degradation (molecular weight, crystallinity, and tack) and strong sensitivity to contamination, leading to property decline after each cycle and often restricting recyclates to applications of lower value or shorter lifespans (Younis et al. 2024). Chemical recycling—depoymerization, dissolution-based separations, pyrolysis, and gasification—promises higher purity and the potential to valorize mixed or multilayer streams, including thermosets and composites; however, it remains energy-intensive, technologically complex, and frequently hampered by high pre-sorting requirements and uncertain techno-economic viability at scale (Srivastava 2025). A pragmatic view emerging from systems-level analyses documents that no single recycling pathway suffices for the broad spectrum of polymer waste generated by buildings; instead, a tiered, hybrid approach—combining dissolution or selective delamination for separation, followed by targeted chemical or mechanical routes—offers the best potential for maintaining material quality across cycles while reducing lifecycle carbon (McGuire et al. 2025). The literature also notes a behavioral and policy gap: current recycling rates fall far short of theoretical recyclability, with persistent barriers including feedstock contamination, nonuniform material design, and fragmented collection, which collectively constrain circularity and limit lifecycle carbon benefits in energy-positive buildings (McGuire et al. 2025).

In sum, advancing the circularity of polymer-based construction materials requires (i) explicit design-for-recycling strategies that reduce heterogeneity and remove non-recyclable tie layers and additives; (ii) scalable, integrated recycling workflows that leverage the strengths and compensate for the weaknesses of both mechanical and chemical routes; and (iii) robust data, standardization, and policy frames to translate theoretical recyclability into real-world rates and lifecycle carbon savings. The gap between ideal recyclability and observed recovery rates remains a major bottleneck for achieving low-carbon, energy-positive buildings, underscoring the need for coordinated advances in material design, processing technologies, and circular economy governance (Adam et al. 2025; McGuire et al. 2025).

7.2. Secondary Raw Materials from Demolition Waste

Demolition waste harbors substantial potential as a feedstock for secondary raw materials, with multiple studies showing that material streams such as recycled aggregates, mineral fractions, metals, glass, and recovered polymers can substitute primary materials in construction. Comparative analyses across case studies and regional contexts indicate that recycled aggregates (RAs) and RCA/RFA fractions can replace conventional coarse and fine aggregates in concrete and road base, albeit with performance constraints tied to particle quality, contamination, and the presence of mortar or ceramics (Shufrin et al. 2023). Metals recovered from structural steel, aluminum, copper, and ferrous alloys consistently demonstrate high recycling rates and embodied-energy benefits when properly segregated, while glass cullet and post-consumer polymers offer potential for asphalt, concrete, and composite applications, provided sorting and cleaning advances accompany collection (Keyhani et al. 2023a). Across these streams, several analyses converge on the notion that end-of-life material streams can close material loops, contributing to resource efficiency and circular economy goals when embedded in design decisions that anticipate deconstruction and material passports (Hussain and Kamal 2015).

Crucially, the literature reveals persistent barriers that limit the realization of lower-embodied-carbon outcomes from demolition-derived secondary materials. Contamination with pre-existing mortars, bricks, plaster, gypsum, and non-target polymers reduces material quality and performance, while mixed waste streams, heterogeneous composition, and variable on-site sorting capabilities hinder assurance of consistent material standards (Baiani and Altamura 2022). Regulatory constraints and the absence of harmonized EPDs or material passports further impede uptake by increasing uncertainty and transaction costs for designers and contractors (Keyhani et al. 2023a). Several studies underscore that while recycling can reduce embodied carbon by avoiding virgin material production, this does not automatically translate into lower lifecycle impacts: the processing energy, transportation, and end-of-life treatment can offset gains if recycling rates are suboptimal or if secondary materials fail to perform adequately and require overdesign or additional substitutes (Vidal et al. 2019). The net climate performance thus hinges on system-level choices—designing for disassembly, incorporating high-recovery pathways, and aligning regulatory and market incentives to sustain quality sorting and validated supply chains (Hussain and Kamal 2015).

In the context of energy-positive buildings and sustainability foundations, secondary materials contribute to circular economy trajectories and resource efficiency by reducing primary material demand and associated embodied carbon, but only when integrated with appropriate governance, validation of material quality, and robust life-cycle accounting. Several studies emphasize that generic labeling of recycled content is insufficient; the carbon and energy benefits depend on concrete performance, end-of-life pathways, and accurate accounting of C3 and D-stage contributions in LCA frameworks. This nuance is highlighted in cross-comparative assessments that compare recycling strategies, energy payback, and lifecycle emissions across materials and regions, illustrating that recycled content must be coupled with strategic design for reuse, disassembly, and credible EPD data to achieve genuine climate-positive outcomes (Keyhani et al. 2023a; Shufrin et al. 2023).

7.3. Design for Disassembly

Design for Disassembly (DfD) is a lifecycle-oriented design discipline that foregrounds end-of-life recoverability by enabling orderly separation of building components and materials for repair, reuse, remanufacturing, or recycling. The literature consistently frames DfD as a critical enabler of circular building practice, linking its success to modular architectures, standardized connections, and careful material compatibility that preserve value across multiple life cycles (Roxas et al. 2023) . Empirical work in the construction sector shows that reversible or demountable connections (bolts, clips, plug-and-play interfaces) and modular subdivision of assemblies substantially lower disassembly effort and material damage, thereby enhancing reuse potential and reducing embodied carbon when compared with conventional, linearly demolished components (Roxas et al. 2023). Case studies of prefabricated envelopes and timber-based systems quantify embodied-carbon reductions and highlight that multi-cycle reuse outcomes hinge on the reversibility of connections and the ability to maintain material condition during recovery (Bergmans et al. 2023). However, several studies emphasize that the climate and circular benefits of DfD are contingent on real-world recovery rates and life-cycle performance, with economic and policy constraints shaping outcomes (e.g., up to 50% embodied-carbon reductions in favorable cases, and clear thresholds where downcycling diminishes climate benefits) (Bergmans et al. 2023).

Material selection, connections, and system integration emerge as the linchpins of disassembly performance. Material compatibility across interfaces—favoring non-toxic, non-composite, and standardizable materials—facilitates off-site management and downstream reuse, while modular design aggregates functions into discrete, interchangeable units that can be disassembled with minimal collateral damage (Roxas et al. 2023). Yet the literature uniformly acknowledges practical limitations: higher initial design complexity and cost, scarcity of standardized DfD guidelines for diverse building systems, and fragmentation in policy uptake and industry practice hinder broad adoption (Roxas et al. 2023). Notably, several analyses connect DfD to the circular economy and lifecycle carbon reduction by demonstrating that modular, reversible connections and strategic material choices enable material banks, multi-life service, and enhanced recovery pathways, underscoring the need for early-stage design decisions and alignment with circular-design metrics (e.g., circularity indicators and Level(s)–compatible assessments) to translate theoretical gains into tangible performance (Roxas et al. 2023). Where governance and standards lag, potential benefits are curtailed, and the literature calls for harmonized criteria, repeatable disassembly workflows, and industry-scale demonstrations to close the gap between design ideals and practice (Roxas et al. 2023).

7.4. Life Cycle Carbon Beyond Operational Balance

Operational carbon and embodied carbon denote distinct portions of a building's total climate impact. Operational carbon arises from energy consumed during use (heating, cooling, lighting, equipment), whereas embodied carbon encompasses emissions from material production, construction, maintenance, and end-of-life across the building's life cycle (Curmi et al. 2022). Across multiple studies, as operational energy intensity falls with high-performance envelopes and on-site renewables, the share of embodied carbon in total life-cycle emissions rises and can dominate the footprint in NZEB/NZCB contexts; e.g., analyses of net-zero or beyond-net-zero designs show embodied emissions can constitute substantial or even majority shares when operating energy is minimized (often 26–74% in low-energy to net-zero scenarios, and up to 74–100% in some net-zero cases) (Keyhani et al. 2023b). Kneifel et al. demonstrate that pursuing net-zero operating performance can trigger a pronounced increase in embodied flows (over 40%), offsetting some operating gains, though total life-cycle emissions still decline relative to code-built baselines; this finding is echoed by systematic reviews noting the growing prominence of EC as OC improves (Keyhani et al. 2023b). More advanced LC-ZCB frameworks explicitly optimize for both OC and EC, sometimes achieving negative life-cycle embodied values when biobased or carbon-storing materials are deployed, but such outcomes hinge on material choice, supply chains, and end-of-life assumptions (Gomes 2025).

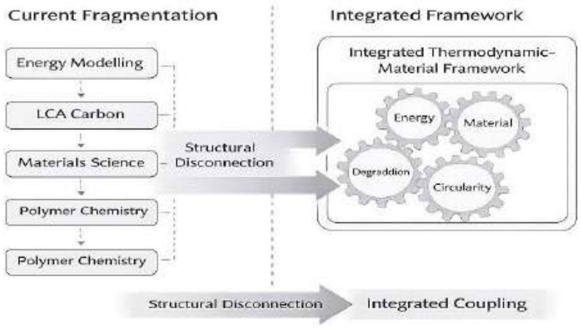
Current approaches that focus predominantly on operational energy metrics risk obscuring where most emissions accumulate, particularly during material production, construction, and end-of-life phases. Several studies emphasize the need to integrate embodied flows into policy and practice; policy reviews and practitioner guides argue for whole-life carbon accounting (WLCA) to guide design decisions, material selection, and demolition versus refurbishment pathways, noting wide cross-country variation in methodologies and definitions of net-zero that can undercount EC if boundaries are poorly defined (Loveday et al. 2022; F. Yu et al. 2022). In practice, refurbishment and reuse can outperform new construction when embedded emissions and end-of-life scenarios are properly accounted for, sometimes yielding lower life-cycle carbon than demolition-rebuild options even under aggressive OC reductions, underscoring the necessity of urban-scale, dynamic LCA approaches and benchmarking to move beyond operational-centric targets (Hu 2021). Collectively, the literature argues for a holistic design paradigm that couples aggressive operational strategies with aggressive embodied-carbon mitigation—through material substitution, circular design for disassembly, and end-of-life strategies—to realize true low or net-zero life-cycle carbon, rather than assuming that zero or near-zero operating energy automatically delivers low lifecycle emissions (Gomes 2025).

8. Research Gaps and Future Directions

8.1. Integrated Energy–Material Modelling

Integrated Energy–Material Modelling: A forward-looking synthesis is needed because current energy-performance assessments for energy-positive buildings treat materials as static inputs rather than chemically and electrochemically responsive systems, leaving a critical gap between building energy models and the molecular- to microstructural properties that govern material performance and degradation under real service conditions (Ding et al. 2022). The lack of coupling between energy simulations and material-level chemical properties undermines the predictive fidelity of sustainability assessments, since changes in material chemistry, microstructure, hydration, degradation pathways, diffusion, and interfacial reactions directly alter thermal conductivity, moisture transport, heat capacity, durability, and embodied energy over the building's life cycle (Q. Ma et al. 2023). A robust framework is required to couple energy simulations with material degradation models, transport phenomena, and interface chemistry to forecast long-term energy performance, repair needs, and end-of-life trajectories; such integration would enable dynamic LCA/LCA-like life-cycle energy accounting that accounts for evolving material states, facilitating design choices that optimize both operational energy and material sustainability across decades (Costa 2025). While some reviews address LCA, durability modelling, or advanced energy-material systems in isolation, there is no consensus on standardized coupling methodologies or data-sharing practices, and harmonized multi-scale, multi-physics approaches are urgently needed to move from static assumptions to predictive, integrated, and auditable assessments for future energy-positive buildings (Nath et al. 2018b). In this direction, future work should emphasize open, interoperable pipelines that link process-level chemistry, degradation kinetics, and microstructure-informed transport with building-scale energy models, supported by validated, scalable simulations and enhanced data transparency to close the loop from material design to lifetime energy performance (Sbahieh et al. 2023). As illustrated in Fig. 7, current research architectures treat energy modelling and materials chemistry as parallel domains. Future frameworks must integrate these into a unified thermodynamic-material system.

Figure 7. Structural contrast between current disciplinary fragmentation and an integrated energy–material–degradation–circularity framework in energy-positive building research.



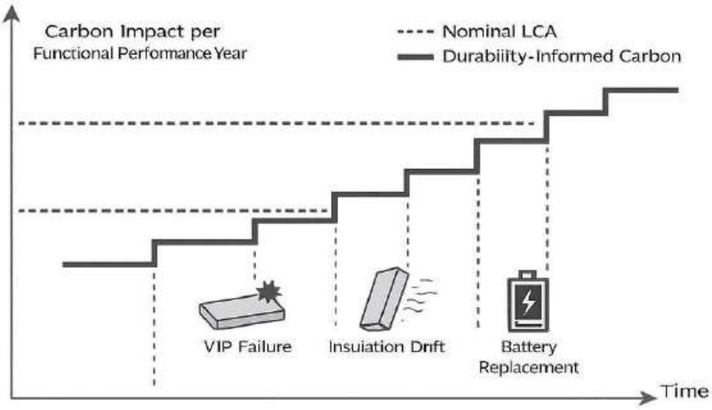
8.2. <u>Exergy-Based Carbon Evaluation</u>

Exergy-based carbon evaluation offers a critical lens to overcome the well-known limitations of energy-based carbon accounting, which conflates energy quantity with environmental impact and often underrepresents the quality of energy flows, irreversibilities, and the ambient conditions under which energy is exchanged; exergy, by quantifying the maximum useful work potential relative to the environment, reveals that two systems with identical energy consumption can have markedly different environmental burdens due to differences in energy quality, transfer losses, and irreversibility (M. Ma et al. 2021), a point reinforced in exergy-LCA integrations that highlight its capacity to unify material, energetic, and environmental dimensions into a common unit and to expose hidden inefficiencies in resource use (M. Ma et al. 2021). Despite this theoretical appeal, the application of exergy-based approaches to building-scale sustainability remains disproportionately underdeveloped, with most exergy work concentrated in civil infrastructure and industrial processes rather than in single buildings or built-environment districts, thereby missing scale- and boundary-specific dynamics such as occupancy-driven load profiles, embodied exergy in materials, and end-of-life couplings that shape long-term resilience and retrofit potential (M. Ma et al. 2021). Consequently, the exergy perspective invites targeted research directions: (i) developing standardized building exergy assessment frameworks that coherently integrate operational, embodied, and end-of-life exergy destruction across lifecycle stages; (ii) coupling exergy metrics with dynamic building energy simulations under climate-change scenarios to capture quality-adjusted demand and supply mismatches; (iii) advancing exergoeconomic and exergoenvironmental analyses for buildings to inform cost-optimized decarbonization pathways; and (iv) designing pilot demonstrations of exergy-based decision-support tools at the neighborhood and district scales to reveal synergies between building design, grid interactions, and circular material strategies, thereby bridging the current gap between exergy theory and practical, energy-positive building outcomes (M. Ma et al. 2021). Annotated bibliography follows.

8.3. Durability-Based Carbon Modelling

Current carbon modelling in built environments largely treats materials and assemblies as static end-states, neglecting how ageing, degradation, and refurbishment reshape embodied and operational emissions over the building lifetime; this gap undermines the reliability of lifecycle carbon estimates and can misinform decarbonization strategies (Kang et al. 2019). Material degradation drives evolving emissions profiles: degradation mechanisms, maintenance, component replacement, and end-of-life recycling loops alter the timing, magnitude, and composition of embodied carbon, often amplifying recurring emissions through more frequent refurbishments even as newer materials promise lower standby footprints (Kang et al. 2019). Consequently, integrating ageing and lifetime into carbon assessments is essential to capture the full spectrum of future emissions, including how future decarbonization of electricity, circular material strategies, and disassembly/reuse pathways interact with aging stocks to modulate long-run carbon outcomes (Moomaw et al. 2020). A forward-looking framework that embeds time-dependent material performance,Stock turnover, and dynamic refurbishment scenarios within LCA/LCC paradigms is therefore needed to produce robust, policy-relevant insights for energy-positive buildings and the chemical foundations of sustainability (Stephan et al. 2022). In doing so, researchers should explicitly address the trade-offs between durability, embodied carbon, and operational carbon, and leverage cross-scale, multistage modeling to anticipate how lifetime extension and material substitution reshape whole-life carbon trajectories under evolving energy systems (Moomaw et al. 2020). As conceptually illustrated in Fig. 8, static life-cycle carbon accounting assumes constant performance over time, whereas durability-informed modelling reflects capacity drift, envelope degradation, and component replacement cycles.

Figure 8. Illustration of divergence between static life-cycle carbon assessment and time-corrected carbon modelling incorporating material degradation and replacement cycles.



8.4. Advanced Polymer Design for Circularity

Advanced Polymer Design for Circularity: The energy-positive trajectory of buildings hinges not only on material performance but on truly circular polymers whose end-of-life is an integral design parameter. Current recyclability and circularity remain hampered by mixed-polymer streams, irreversible crosslinks, and energy-intensive depolymerization pathways that degrade material properties across cycles (Balu et al. 2022). To move beyond this linearity, polymers must be conceived with closed-loop end-of-life in mind—incorporating degradable or recyclable backbones, dynamic covalent networks, and modular architectures that enable property-tunable end-of-life handling without sacrificing performance in service (Mah et al. 2025). Emerging approaches—recyclable thermosets and vitrimers, covalent adaptable networks, and depolymerization/upcycling strategies—offer routes to recover monomers or convert waste into value-added materials while preserving or enhancing functionality (Balu et al. 2022; Ellis et al. 2021; Habets et al. 2023; H. J. Kim 2023; Y. Ma et al. 2022). Realization will require design principles that balance mechanical resilience with controllable bond exchange kinetics, renewable-sourced monomers, and compatible processing to support energy-positive buildings under a cradle-to-cradle paradigm (Y. Ma et al. 2022; Mah et al. 2025). While challenges persist—such as achieving selective depolymerization in mixed waste streams and scaling dynamic chemistries to industrial volumes—a concerted emphasis on end-of-life design and integrated lifecycle thinking will enable a future where building polymers contribute to sustained energy efficiency, resource security, and environmental regeneration (Shahriari and Kim 2025).

8.5. Material Constraints in Hydrogen Systems

Material constraints in hydrogen systems are a primary bottleneck to the energy-positive buildings vision, as material choices govern the safety, durability, and economic viability of electrolysis, storage, and fuel cells that underpin building-scale hydrogen integration; in electrolysis, durable, cost-effective electrodes and membranes must withstand aggressive operating environments across alkaline, PEM, AEM, and solid-oxide platforms, while catalyst scarcity and degradation under repeated cycling threaten overall efficiency and system life, signaling a need for alternative materials, catalysts, and protective coatings (Guan et al. 2023); in storage, high-pressure tanks, cryogenic or solid-state storage, and potential regenerative or LOHC approaches expose embrittlement risks, thermal-management challenges, and weight/material cost trade-offs that constrain volumetric energy density and safety standards essential for building applications, with material compatibility and long-term aging modeling becoming critical for predictable performance (Ahad et al. 2023); in fuel cells, membrane durability, catalyst loss, and stack integration remain cost and lifetime bottlenecks that impede rapid deployment in building envelopes or campus-scale microgrids, underscoring the imperative for cross-cutting materials research—novel catalysts, membranes with lower precious-metal loading, advanced heat and mass transfer architectures, and integrative designs that harmonize electrolyzer, storage, and fuel-cell subsystems within the building energy continuum (Hassan et al. 2023). Collectively, these material challenges demand targeted, building-scale research into robust, safe, and cost-competitive materials that enable reliable, continuous hydrogen production, storage, and utilization in energy-positive buildings, while recognizing that technoeconomic constraints and safety governance may intensify as system complexity and scale increase (Kiani et al. 2025).

8.6. Integrated Thermodynamic–Material Design

To advance energy-positive buildings, it is essential to fuse rigorous thermodynamic analysis with materials design, ensuring that high-level system optimization is grounded in feasible, low-level material constraints and failure modes; without this integration, system gains can be severely undermined by exergy losses, material degradations, or incompatible interfaces that erode overall performance (Demirel et al. 2019). A persistent gap remains between architecture-level objectives—such as minimizing exergy destruction and maximizing energy throughput within circular economy constraints—and the realities of material selection, processing limits, and durability under varied climatic and load conditions, which can skew or invalidate optimized solutions when unconstrained by material realities (Weber et al. 2022). We propose a forward-looking framework that couples multi-scale process synthesis and heat–energy integration with materials-intrinsic models through a unified, constraint-aware platform: (i) a modular, building-block representation that spans chemistry, kinetics, exergy, and thermodynamics at the material level; (ii) a system-level optimizer that informs material criteria (e.g., degradability, recyclability, exergy efficiency) via integrated exergy accounting and circularity metrics; and (iii) an iterative design loop wherein material discovery, property prediction (thermodynamic and kinetic), and process integration co-evolve under shared objective functions, enabling rapid convergence to solutions that are both thermodynamically optimal and practically realizable in energy-positive buildings. This blended paradigm harnesses digital-twin–driven simulations, multiscale modeling, and data-enabled decision frameworks to move beyond isolated optimizations toward resilient, scalable, and sustainable building systems (Liu et al. 2025). By explicitly aligning system- and material-level perspectives, future work can close the gap between holistic performance and material constraints, enabling integrated thermodynamic–material design that accelerates the deployment of truly energy-positive buildings.

9. Conclusions

The findings of this review demonstrate that the sustainability of energy-positive buildings cannot be adequately evaluated through operational energy performance alone. Across the literature synthesized here, a consistent pattern emerges: while advances in building energy systems—particularly photovoltaics, electrochemical storage, and hydrogen integrationenable substantial reductions in operational emissions, material-related factors increasingly dominate lifecycle outcomes. Embodied carbon associated with material production, especially in cementitious and polymer-based systems, remains a critical determinant of total environmental impact, often offsetting gains achieved through improved operational efficiency. As operational energy demand declines, the relative importance of embodied emissions rises, underscoring the need to move beyond energy-centric performance metrics toward comprehensive lifecycle-based assessments.

A central insight emerging from this synthesis is that material chemistry fundamentally shapes building sustainability over time. The interplay between molecular design, material composition, and system-level performance reveals that micro-scale properties—such as thermal behavior, chemical stability, and transport characteristics—directly influence macro-scale outcomes, including energy demand, durability, and carbon footprint. This relationship is evident across material categories: from cement systems constrained by calcination emissions, to polymer-based insulation balancing energy efficiency with toxicity and end-of-life challenges, and bio-based materials offering potential benefits but limited by durability and environmental trade-offs. Collectively, the literature highlights that no single material pathway guarantees sustainability; instead, performance depends on context-specific integration across the full lifecycle.

Durability and degradation processes further complicate the sustainability narrative by introducing time-dependent variability into building performance. Chemical ageing, moisture-induced degradation, and photodegradation collectively alter material properties, often accelerating performance decline and increasing maintenance or replacement requirements. These processes directly influence lifecycle carbon by shortening service life and amplifying embodied emissions through repeated interventions. Importantly, discrepancies between laboratory performance and real-world behavior highlight a critical limitation in current assessment approaches, where simplified or isolated testing conditions fail to capture the synergistic effects of environmental exposure. This gap reinforces the need to explicitly incorporate long-term material stability into both design and lifecycle evaluation frameworks.

Circularity and end-of-life considerations represent another key dimension shaping the sustainability of energy-positive buildings. While recycling, secondary material use, and design for disassembly offer pathways to reduce embodied carbon, the literature consistently reveals a gap between theoretical potential and practical implementation. Material heterogeneity, contamination, degradation, and insufficient standardization limit effective recycling and reuse, particularly for polymer-based systems. Similarly, the benefits of secondary raw materials and disassembly-oriented design depend strongly on recovery rates, material quality, and system-level integration. These findings indicate that circularity cannot be treated as an add-on strategy but must be embedded in material selection, design, and lifecycle planning from the outset.

Taken together, the evidence points toward a fundamental need for integration across scales and disciplines. Current approaches remain fragmented, often separating material science, energy systems, and lifecycle assessment into parallel domains. However, the synthesis presented in this review demonstrates that meaningful sustainability gains require a unified framework in which material design, degradation behavior, energy system performance, and lifecycle carbon are considered simultaneously. This integration is particularly critical for emerging technologies such as advanced polymers, thermal storage materials, electrochemical systems, and hydrogen-based infrastructures, where material constraints and system performance are tightly coupled.

Ultimately, the transition toward truly sustainable energy-positive buildings requires a paradigm shift from performance-based evaluation to integrated, multi-scale design thinking. Rather than optimizing individual components in isolation, future building systems must be conceived as interconnected material–energy systems, where chemical design, durability, circularity, and energy performance are co-optimized over the full lifecycle. In this context, sustainability is not solely a function of energy balance, but the outcome of coordinated decisions spanning molecular structure, material systems, and building-scale operation. Only through such an integrated perspective can energy-positive buildings evolve from a promising concept into a robust and genuinely low-carbon solution for the built environment.

References

Adam, Hermann, Mohamed Yousfi, Abderrahim Maazouz, and Khalid Lamnawar. 2025. ‘Recycling of Multilayer Polymeric Barrier Films: An Overview of Recent Pioneering Works and Main Challenges’. *Macromolecular Materials and Engineering* 310 (7). https://doi.org/10.1002/mame.202400414.

Ahad, Abdul, Md M. H. Bhuiyan, Ahmed N. Sakib, Alfredo B. Corral, and Zahed Siddique. 2023. ‘An Overview of Challenges for the Future of Hydrogen’. *Materials* 16 (20): 6680. https://doi.org/10.3390/ma16206680.

Akarken, Gürkan, Yetkin Yildirim, and Uğur Cengiz. 2025. ‘Innovative Geopolymer Tiles for Indoor Humidity Control: A Comparative Study of Moisture Buffering Performance’. *Acs Omega* 10 (9): 9197–209. https://doi.org/10.1021/acsomega.4c09422.

Almalioti S., Tsiotas D., 2025. “Structural characteristics of the OECD international trade network and their association with economic development”, Sustainable Regional Development Scientific Journal, Vol II. (2), pp.21-32

Alrehaili, Eman, Anissa Nurdiawati, and Sami G. Al-Ghamdi. 2025. ‘Sustainable Composites for Metal Replacement: Environmental Assessment and Material Selection of Fiber-Reinforced Polymer across Industries’. *Resources, Conservation & Recycling Advances* 28 (December): 200294. https://doi.org/10.1016/j.rcradv.2025.200294.

Andersen, Camilla M. E., Freja N. Rasmussen, Guillaume Habert, and Harpa Birgisdóttir. 2021. ‘Embodied GHG Emissions of Wooden Buildings—Challenges of Biogenic Carbon Accounting in Current LCA Methods’. *Frontiers in Built Environment* 7. https://doi.org/10.3389/fbuil.2021.729096.

Andrady, Anthony L., Anu Heikkilä, Krishna K. Pandey, et al. 2023. ‘Effects of UV Radiation on Natural and Synthetic Materials’. *Photochemical & Photobiological Sciences* 22 (5): 1177–202. https://doi.org/10.1007/s43630-023-00377-6.

Arvizu-Montes, A., Oswaldo Guerrero-Bustamante, Rodrigo Polo-Mendoza, and M. J. Martinez-Echevarria. 2025. ‘Integrating Life-Cycle Assessment (LCA) and Artificial Neural Networks (ANNs) for Optimizing the Inclusion of Supplementary Cementitious Materials (SCMs) in Eco-Friendly Cementitious Composites: A Literature Review’. *Materials* 18 (18): 4307. https://doi.org/10.3390/ma18184307.

Baiani, Serena, and Paola Altamura. 2022. *Reusable Cities: A Circular Design Approach to Urban Regeneration Through Materials Reuse*. https://doi.org/10.5772/intechopen.105219.

Balu, Rajkamal, Naba K. Dutta, and Namita R. Choudhury. 2022. ‘Plastic Waste Upcycling: A Sustainable Solution for Waste Management, Product Development, and Circular Economy’. *Polymers* 14 (22): 4788. https://doi.org/10.3390/polym14224788.

Berdahl, Paul, Hashem Akbari, Ronnen Levinson, and William A. Miller. 2008. ‘Weathering of Roofing Materials – An Overview’. *Construction and Building Materials* 22 (4): 423–33.

https://doi.org/10.1016/j.conbuildmat.2006.10.015.

Bergmans, Ivar, Silu Bhochhibhoya, and John v. Oorschot. 2023. 'Assessing the Circular Re-Design of Prefabricated Building Envelope Elements for Carbon Neutral Renovation'. *Journal of Facade Design and Engineering* 11 (2): 169–96. https://doi.org/10.47982/jfde.2023.2.a4.

Blinova, Ekaterina, Tatyana V. Ponomarenko, and Sofiya Tesovskaya. 2023. 'Key Corporate Sustainability Assessment Methods for Coal Companies'. *Sustainability* 15 (7): 5763. https://doi.org/10.3390/su15075763.

Booth, Peter, and Ljubomir Jankovic. 2022. 'Novel Biodesign Enhancements to At-Risk Traditional Building Materials'. *Frontiers in Built Environment* 8. https://doi.org/10.3389/fbuil.2022.766652.

Bošnjaković, Mladen, Marko Katinić, Ante Čikić, and Simon Muhič. 2023. 'Building Integrated Photovoltaics. Overview of Barriers and Opportunities'. *Thermal Science* 27 (2 Part B): 1433–51. https://doi.org/10.2298/tsci221107030b.

Cabeza, Luisa F., Laura Boquera, Marta Chàfer, and David Vérez. 2021. 'Embodied Energy and Embodied Carbon of Structural Building Materials: Worldwide Progress and Barriers Through Literature Map Analysis'. *Energy and Buildings* 231: 110612. https://doi.org/10.1016/j.enbuild.2020.110612.

Cai, Hao, Xinyi Wang, Jarod C. Kelly, and Michael Wang. 2021. *Building Life-Cycle Analysis With the GREET Building Module: Methodology, Data, and Case Studies*. https://doi.org/10.2172/1823607.

Caldeira, Carla, Elisabetta Abbate, Christian Moretti, Lucia Mancini, and Serenella Sala. 2024. 'Safe and Sustainable Chemicals and Materials: A Review of Sustainability Assessment Frameworks'. *Green Chemistry* 26 (13): 7456–77. https://doi.org/10.1039/d3gc04598f.

Cheekatamarla, Praveen. 2024. 'Hydrogen and the Global Energy Transition—Path to Sustainability and Adoption Across All Economic Sectors'. *Energies* 17 (4): 807. https://doi.org/10.3390/en17040807.

Chen, Zhongjia, Hongmei Gu, Richard Bergman, and Shaobo Liang. 2020. 'Comparative Life-Cycle Assessment of a High-Rise Mass Timber Building With an Equivalent Reinforced Concrete Alternative Using the Athena Impact Estimator for Buildings'. *Sustainability* 12 (11): 4708. https://doi.org/10.3390/su12114708.

Coffaro, Breann, and Clifford P. Weisel. 2022. 'Reactions and Products of Squalene and Ozone: A Review'. *Environmental Science & Technology* 56 (12): 7396–411. https://doi.org/10.1021/acs.est.1c07611.

Concrete in the Marine Environment'. *Energy and Buildings* 158: 1694–702. https://doi.org/10.1016/j.enbuild.2017.12.011.

Costa, Renata. 2025. 'Life Cycle Assessment (LCA) Challenges in Evaluating Emerging Battery Technologies: A Review'. *Materials* 18 (18): 4321. https://doi.org/10.3390/ma18184321

Curmi, Lachlan, Kumudu K. Weththasinghe, and Muhammad Atiq Ur Rehman Tariq. 2022. 'Global Policy Review on Embodied Flows: Recommendations for Australian Construction Sector'. *Sustainability* 14 (21): 14628. https://doi.org/10.3390/su142114628.

Demirel, Salih E., Jianping Li, and M. M. F. Hasan. 2019. 'A General Framework for Process Synthesis, Integration, and Intensification'. *Industrial & Engineering Chemistry Research* 58 (15): 5950–67. https://doi.org/10.1021/acs.iecr.8b05961.

Ding, Yu, Zhenqian Pang, Kai Lan, et al. 2022. 'Emerging Engineered Wood for Building Applications'. *Chemical Reviews* 123 (5): 1843–88. https://doi.org/10.1021/acs.chemrev.2c00450.

Dove, Cassandra A., Fiona F. Bradley, and Siddharth V. Patwardhan. 2019. 'A Material Characterization and Embodied Energy Study of Novel Clay-Alginate Composite Aerogels'. *Energy and Buildings* 184: 88–98. https://doi.org/10.1016/j.enbuild.2018.10.045.

Ellis, Lucas D., Nicholas A. Rorrer, Kevin P. Sullivan, et al. 2021. 'Chemical and Biological Catalysis for Plastics Recycling and Upcycling'. *Nature Catalysis* 4 (7): 539–56. https://doi.org/10.1038/s41929-021-00648-4.

Felmer, Gabriel, Rodrigo Morales-Vera, Rodrigo Astroza, Ignacio González, Maureen Puettmann, and Mark Wishnie. 2022. 'A Lifecycle Assessment of a Low-Energy Mass-Timber Building and Mainstream Concrete Alternative in Central Chile'. *Sustainability* 14 (3): 1249. https://doi.org/10.3390/su14031249.

FJ Teixeira, SSPV Pescada, F Ruxho, C Palma, F Beha, 2024, GLAMPING IN LOW-DENSITY TERRITORIES: THE CASE OF SANTO ALEIXO DA REASTAURA?? O, Regional Science Inquiry 16 (1), 71-80

Gao, Zhenhai, Haicheng Xie, Xianbin Yang, et al. 2023. 'Electric Vehicle Lifecycle Carbon Emission Reduction: A Review'. *Carbon Neutralization* 2 (5): 528–50. https://doi.org/10.1002/cnl2.81.

Goh, Cheng S., and S. T. Ng. 2016. 'Developing Key Parameters for Green Performance of Partition

Wall Blocks'. *Matec Web of Conferences* 68: 13007. https://doi.org/10.1051/matecconf/20166813007.

Gomes, V. 2025. 'A State of Play Review of Methods to Define Net Zero Carbon Buildings'. *Iop Conference Series Earth and Environmental Science* 1554 (1): 012132. https://doi.org/10.1088/1755-1315/1554/1/012132.

Guan, Daqin, Bowen Wang, Jiguang Zhang, et al. 2023. 'Hydrogen Society: From Present to Future'. *Energy & Environmental Science* 16 (11): 4926–43. https://doi.org/10.1039/d3ee02695g.

Habets, Thomas, Guillem Seychal, Marco Caliari, et al. 2023. 'Covalent Adaptable Networks Through Dynamic N , S -Acetal Chemistry: Toward Recyclable CO 2 -Based Thermosets'. *Journal of the American Chemical Society* 145 (46): 25450–62. https://doi.org/10.1021/jacs.3c10080.

Hammond, Geoffrey, Craig Jones, Fiona Lowrie, and Peter Tse. 2011. *Embodied Carbon: The Inventory of Carbon and Energy (ICE)*. BSRIA.

Hassan, Qusay, Itimad D. J. Azzawi, Aws Z. Sameen, and Hayder M. Salman. 2023. 'Hydrogen Fuel Cell Vehicles: Opportunities and Challenges'. *Sustainability* 15 (15): 11501. https://doi.org/10.3390/su151511501.

Hu, Ming. 2021. 'Beyond Operational Energy Efficiency: A Balanced Sustainability Index From a Life Cycle Consideration'. *Sustainability* 13 (20): 11263. https://doi.org/10.3390/su132011263.

Huang, Jintao, Yue Luo, Mengman Weng, et al. 2021. 'Advances and Applications of Phase Change Materials (PCMs) and PCMs-Based Technologies'. *Es Materials & Manufacturing*, ahead of print. https://doi.org/10.30919/esmm5f458.

Hussain, Anwar, and Mohammad A. Kamal. 2015. 'Energy Efficient Sustainable Building Materials: An Overview'. *Key Engineering Materials* 650: 38–50. https://doi.org/10.4028/www.scientific.net/kem.650.38.

Iwuanyanwu, Obinna, Ifechukwu Gil-Ozoudeh, Azubuike C. Okwandu, and Chidiebere S. Ike. 2024. 'The Role of Green Building Materials in Sustainable Architecture: Innovations, Challenges, and Future Trends'. *International Journal of Applied Research in Social Sciences* 6 (8): 1935–50. https://doi.org/10.51594/ijarss.v6i8.1476.

Jacobs, Deborah S., Sin-Ru Huang, Yu-Lun Cheng, et al. 2016. 'Surface Degradation and Nanoparticle Release of a Commercial Nanosilica/Polyurethane Coating Under UV Exposure'. *Journal of Coatings Technology and Research* 13 (5): 735–51. https://doi.org/10.1007/s11998-016-9796-2.

Jones, Christopher, Paul Gilbert, and Laurence Stamford. 2019. 'Assessing the Climate Change Mitigation Potential of Stationary Energy Storage for Electricity Grid Services'. *Environmental Science & Technology* 54 (1): 67–75. https://doi.org/10.1021/acs.est.9b06231.

Kang, Goune, Hunhee Cho, and Dongyoun Lee. 2019. 'Dynamic Lifecycle Assessment in Building Construction Projects: Focusing on Embodied Emissions'. *Sustainability* 11 (13): 3724. https://doi.org/10.3390/su11133724.

Kayan, Brit A., A. Förster, and Phillip F. G. Banfill. 2016. 'Green Maintenance for Historic Masonry Buildings: An Option Appraisal Approach'. *Smart and Sustainable Built Environment* 5 (2): 143–64. https://doi.org/10.1108/sasbe-05-2015-0010.

Keyhani, Maryam, Atefeh Abbaspour, Ali Bahadori-Jahromi, et al. 2023a. 'Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources'. *Sustainability* 15 (6): 5115. https://doi.org/10.3390/su15065115.

Keyhani, Maryam, Atefeh Abbaspour, Ali Bahadori-Jahromi, et al. 2023b. 'Whole Life Carbon Assessment of a Typical UK Residential Building Using Different Embodied Carbon Data Sources'. *Sustainability* 15 (6): 5115. https://doi.org/10.3390/su15065115.

Khan A., Tripathi S., Chandiramani J., 2024. "Smart city initiatives and economic growth in india: an empirical analysis", Sustainable Regional Development Scientific Journal, Vol. I, (2): Special Issue, pp. 41-56

Kiani, Maryam, Yanling Zhao, and Ruiqin Zhang. 2025. 'Proton Exchange Membrane Fuel Cells: Recent Developments and Future Perspectives'. *Chemical Communications* 61 (52): 9392–411. https://doi.org/10.1039/d5cc01478f.

Kim, Donggyun, Hyunsoo Lim, Sung H. Kim, et al. 2024. 'Recent Developments of Polymer-Based Encapsulants and Backsheets for Stable and High-Performance Silicon Photovoltaic Modules: Materials Nanoarchitectonics and Mechanisms'. *Journal of Materials Chemistry A* 12 (13): 7452–69. https://doi.org/10.1039/d3ta06130b.

Kim, Hee J. 2023. *Current Advances and Challenges in Chemical Recycling of Polymeric Materials*. https://doi.org/10.20944/preprints202310.0427.v1.

Kirk, Alexander P. 2022. *Contemplating Terawatts of Renewable Electricity and the Need for Improved Energy Efficiency and Reduced Energy Demand in the U.S.* https://doi.org/10.31219/osf.io/b49sa.

Kong, Jiashu, Yitong Dong, Aravind Poshnath, Behzad Rismanchi, and Pow-Seng Yap. 2023. 'Application of Building Integrated Photovoltaic (BIPV) in Net-Zero Energy Buildings

(NZEBs)’. *Energies* 16 (17): 6401. https://doi.org/10.3390/en16176401.

Krupavicius, A., Šarkute, L., Krasniqi, A., Ladias, Christos Ap. 2024. “Perceived and desired images of society: how (un)equal is society?” Regional Science Inquiry, 16(1), pp. 55-70

Lausselet, Carine, Linda A. Ellingsen, Anders H. Strømman, and Helge Brattebø. 2019. ‘A Life-cycle Assessment Model for Zero Emission Neighborhoods’. *Journal of Industrial Ecology* 24 (3): 500–516. https://doi.org/10.1111/jiec.12960.

Lee, Myung K., Min O. Kim, T. C. Lee, et al. 2025. ‘Epoxy-Based Vitrimers for Sustainable Infrastructure: Emphasizing Recycling and Self-Healing Properties’. *Polymers* 17 (3): 373. https://doi.org/10.3390/polym17030373.

Lincaru C., Tudose G., Cosnita D., Pirciog S., Grigorescu A., Ciuca V., 2024. “Clusters as engines of sustainable employment growth in Romania1”, Sustainable Regional Development Scientific Journal, Vol. I, (3), pp. 10-27

Liu, Meng, Xin Xie, Wenhui Yang, et al. 2025. ‘A Two-level Optimal Scheduling Control Strategy for Air Source Heat Pump Loads With Phase Change Energy Storage’. *Iet Generation Transmission & Distribution* 19 (1). https://doi.org/10.1049/gtd2.70004.

Lobaccaro, Gabriele, Aoife H. Wiberg, Giulia Ceci, Mattia Manni, Nicola Lolli, and Umberto Berardi. 2018. ‘Parametric Design to Minimize the Embodied GHG Emissions in a ZEB’. *Energy and Buildings* 167: 106–23. https://doi.org/10.1016/j.enbuild.2018.02.025.

Loveday, Jane, Gregory M. Morrison, and David A. Martin. 2022. ‘Identifying Knowledge and Process Gaps From a Systematic Literature Review of Net-Zero Definitions’. *Sustainability* 14 (5): 3057. https://doi.org/10.3390/su14053057.

Ma, Mingjun, Ziqiao Li, Kai Xue, and Meng Liu. 2021. ‘Exergy-Based Life Cycle Assessment Model for Evaluating the Environmental Impact of Bridge: Principle and Case Study’. *Sustainability* 13 (21): 11804. https://doi.org/10.3390/su132111804.

Ma, Qiang, Xianglong Zhang, Jie Li, et al. 2023. ‘Transition Metal Catalysts for Atmospheric Heavy Metal Removal: A Review of Current Innovations and Advances’. *Molecules* 28 (22): 7620. https://doi.org/10.3390/molecules28227620.

Ma, Youwei, Xuesong Jiang, Jie Yin, Christoph Weder, José A. Berrocal, and Zixing Shi. 2022. ‘Chemical Upcycling of Conventional Polyureas Into Dynamic Covalent Poly(Aminoketoenamide)s’. *Angewandte Chemie International Edition* 135 (3). https://doi.org/10.1002/ange.202212870.

Maghrabie, Hussein M., Mohammad A. Abdelkareem, Abdul H. Alami, et al. 2021. ‘State-of-the-Art Technologies for Building-Integrated Photovoltaic Systems’. *Buildings* 11 (9): 383. https://doi.org/10.3390/buildings11090383.

Mah, Justin J. Q., Nayli E. B. Surat’man, Bofan Li, Sheng Wang, and Zibiao Li. 2025. ‘Recent Advances of Dynamic Covalent Chemistry Polymers Aligning With Principles of Green Chemistry’. *Chemsuschem* 18 (14). https://doi.org/10.1002/cssc.202500480.

Maraveas, Chrysanthos. 2020. ‘Environmental Sustainability of Plastic in Agriculture’. *Agriculture* 10 (8): 310. https://doi.org/10.3390/agriculture10080310.

Marín-Calvo, Nacarí, Sergio González-Serrud, and Arthur James-Rivas. 2023. ‘Thermal Insulation Material Produced From Recycled Materials for Building Applications: Cellulose and Rice Husk-Based Material’. *Frontiers in Built Environment* 9. https://doi.org/10.3389/fbuil.2023.1271317.

McGuire, Thomas M., David Ning, Antoine Buchard, and Charlotte K. Williams. 2025. ‘The Science of Polymer Chemical Recycling Catalysis: Uncovering Kinetic and Thermodynamic Linear Free Energy Relationships’. *Journal of the American Chemical Society* 147 (26): 22734–46. https://doi.org/10.1021/jacs.5c04603.

Moomaw, William R., B. E. Law, and S. J. Goetz. 2020. ‘Focus on the Role of Forests and Soils in Meeting Climate Change Mitigation Goals: Summary’. *Environmental Research Letters* 15 (4): 045009. https://doi.org/10.1088/1748-9326/ab6b38.

Nasr, Yara, Henri E. Zakhem, Ameur E. A. Hamami, Makram E. Bachawati, and Rafik Belarbi. 2023. ‘Comprehensive Review of Innovative Materials for Sustainable Buildings’ Energy Performance’. *Energies* 16 (21): 7440. https://doi.org/10.3390/en16217440.

Nath, Pradip, Prabir K. Sarker, and Wahidul K. Biswas. 2018a. ‘Effect of Fly Ash on the Service Life, Carbon Footprint and Embodied Energy of High Strength Concrete in the Marine Environment’. *Energy and Buildings* 158: 1694–702. https://doi.org/10.1016/j.enbuild.2017.12.011.

Nath, Pradip, Prabir K. Sarker, and Wahidul K. Biswas. 2018b. ‘Effect of Fly Ash on the Service Life, Carbon Footprint and Embodied Energy of High Strength

Nordby, Anne S., and Andrew Shea. 2013. ‘Building Materials in the Operational Phase’. *Journal of Industrial Ecology* 17 (5): 763–76. https://doi.org/10.1111/jiec.12046.

Orr, John, Orlando Gibbons, and Will Arnold. 2020. ‘A Brief Guide to Calculating Embodied Carbon’. *The Structural Engineer* 98 (7): 22–27. https://doi.org/10.56330/JZNX5709.

Pamenter, Sarah, and Rupert J. Myers. 2021. ‘Decarbonizing the Cementitious Materials Cycle: A Whole-systems Review of Measures to Decarbonize the Cement Supply Chain in the UK and European Contexts’. *Journal of Industrial Ecology* 25 (2): 359–76. https://doi.org/10.1111/jiec.13105.

Papajorgji P., Tordi A., 2024. “Using quantitative tools to understand political issues”, Sustainable Regional Development Scientific Journal, Vol. I, (3), pp. 28-35

Pescada S., Correia I., Teixeira F., Ruxho F., 2025. “Social and territorial impacts of the integrated participation programme in Bela Vista”, Sustainable Regional Development Scientific Journal, Vol II. (2), pp.67-74

Pescada S., Serrario M., Sequeira B., Teixeira F., Ladias Ap. C. Ruxho F., 2025. “Safety culture and continuing care”, Sustainable Regional Development Scientific Journal, Vol II. (2), pp.33-44

Peti, Damián, Jozef Dobránsky, and Peter Michalík. 2025. ‘Recent Advances in Polymer Recycling: A Review of Chemical and Biological Processes for Sustainable Solutions’. *Polymers* 17 (5): 603. https://doi.org/10.3390/polym17050603.

Polo A., Beha F., Caca E., Zyberi I., 2025. “Foreign direct investment in real estate and its impact on tourism development in Albania”, Sustainable Regional Development Scientific Journal, Vol II. (2), pp.12-20

Polo A., Caca E., Zyberi I., Ladias C.A, Ruxho F., 2025. “Foreign direct investment in real estate in Albania and its impact on GDP”, Regional Science Inquiry, Vol. XVII, (1), 2025, pp. 135-142

Raja, Pradeep, Vignesh Murugan, Sindhu Ravichandran, et al. 2023. ‘A Review of Sustainable Bio-Based Insulation Materials for Energy-Efficient Buildings’. *Macromolecular Materials and Engineering* 308 (10). https://doi.org/10.1002/mame.202300086.

Ramachandran, Karthikeyan, Constance L. Gnanasagaran, and Ashish Vekariya. 2023. ‘Life Cycle Assessment of Carbon Fiber and Bio-Fiber Composites Prepared via Vacuum Bagging Technique’. *Journal of Manufacturing Processes* 89 (March): 124–31. https://doi.org/10.1016/j.jmapro.2023.01.068.

Ramakrishna, Seeram, Muhammad Pervaiz, Jimi Tjong, Patrizia Ghisellini, and Mohini Sain. 2021. ‘Low-Carbon Materials: Genesis, Thoughts, Case Study, and Perspectives’. *Circular Economy and Sustainability* 2 (2): 649–64. https://doi.org/10.1007/s43615-021-00135-9.

Ramamurthy, K., E. K. Kunhanandan Nambiar, and G. Indu Siva Ranjani. 2009. ‘A Classification of Studies on Properties of Foam Concrete’. *Cement and Concrete Composites* 31 (6): 388–96. https://doi.org/10.1016/j.cemconcomp.2009.04.006.

Rana, Zuraiz, P. P. Zamora, Álvaro Soliz, et al. 2025. ‘Solar Panel Corrosion: A Review’. *International Journal of Molecular Sciences* 26 (13): 5960. https://doi.org/10.3390/ijms26135960.

Real, Luís Eduardo Pimentel. 2023. *Recycled Materials for Construction Applications: Plastic Products and Composites*. 1st ed. 2023. Springer International Publishing. https://doi.org/10.1007/978-3-031-14872-9.

Reddy, Vennapusa J., N. P. Hariram, Mohd F. Ghazali, and K. Sudhakar. 2024. ‘Pathway to Sustainability: An Overview of Renewable Energy Integration in Building Systems’. *Sustainability* 16 (2): 638. https://doi.org/10.3390/su16020638.

Reis, Daniel C., Marco Quattrone, Jhonathan Fernandes Torres de Souza, Katia R. G. Punhagui, Sérgio A. Pacca, and Vanderley M. John. 2021. ‘Potential CO 2 Reduction and Uptake Due to Industrialization and Efficient Cement Use in Brazil by 2050’. *Journal of Industrial Ecology* 25 (2): 344–58. https://doi.org/10.1111/jiec.13130.

Roxas, Cheryl L. C., Carluz R. Bautista, Orlean G. D. Cruz, et al. 2023. ‘Design for Manufacturing and Assembly (DfMA) and Design for Deconstruction (DfD) in the Construction Industry: Challenges, Trends and Developments’.*Buildings* 13 (5): 1164. https://doi.org/10.3390/buildings13051164.

Ruxho F., 2024. “Kosovo employee’s perception of economic growth and decent work according to sustainability”, Sustainable Regional Development Scientific Journal, Vol. I, (3), pp. 53-66

Ruxho F., Ladias C.A, 2022. “Increasing funding for the regional industry of Kosovo and impact on economic growth” Regional Science Inquiry Journal, Vol. XIV. (1), pp. 117-126

Ruxho F., Ladias C.A, Tafarshiku A., Abazi E., 2023. “Regional employee’s perceptions on decent work and economic growth: labour market of Albania and Kosovo”, Regional Science Inquiry, Vol. XV, (2), pp.13-23.

Ruxho F., Ladias C.A., 2022. “The logistic drivers as a powerful performance indicator in the development of regional companies of Kosovo” Regional Science Inquiry Journal, Vol. XIV. (2), pp. 95-106

Ruxho F., Petropoulos D., Negoro D.A. 2024. “Public debt as a determinant of the economic growth in Kosovo”, Sustainable Regional Development Scientific Journal, Vol. I, (1), pp. 55-67

Sarkute L., Sina D., Bello, K., Vercuni A., 2024. “Strategic management decisions in the context of foreign direct investment. The role of institutions and economic determinants”, Sustainable

Regional Development Scientific Journal, Vol. I, (1), pp. 40-54

Sbahieh, Sami, Gordon McKay, and Sami G. Al-Ghamdi. 2023. ‘A Comparative Life Cycle Assessment of Fiber-Reinforced Polymers as a Sustainable Reinforcement Option in Concrete Beams’. *Frontiers in Built Environment* 9. https://doi.org/10.3389/fbuil.2023.1194121.

Scrivener, Karen, Vanderley M. John, and E. M. Gartner. 2018. ‘Eco-Efficient Cements: Potential Economically Viable Solutions for a Low-Co2 Cement-Based Materials Industry’. *Cement and Concrete Research* 114: 2–26. https://doi.org/10.1016/j.cemconres.2018.03.015.

Sejdini In., Sejdini Im., Todri A., Papajorgji P., Ladias C.A., Ruxho F., 2025. “Advancing a new era in higher education management: A stakeholder overview analysis from European and EU non-countries”, Regional Science Inquiry, Vol. XVII, (2), 2025, pp. 11-23 11

Sepetis A., Krupavičius A., Ladias Ap. C. 2024 “Social protection in Greece and sustainable development leaving no one behind”, Sustainable Regional Development Scientific Journal, Vol. I, (1), pp. 83-92

Sequeira T., Rego C., Dionisio A., 2024. “Investment and productivity in the agro-industrial sector: a case study”, Sustainable Regional Development Scientific Journal, Vol. I, (2): Special Issue, pp. 13-26

Shahriari, Leila, and Sungjin Kim. 2025. ‘Toward Circular Polymer Materials and Manufacturing: Dynamic Bonding Strategies for Upcycling Thermoplastics and Thermosets’. *Macromolecular Rapid Communications* 46 (16). https://doi.org/10.1002/marc.202401011.

Sharma, Akhil, Sonu Sharma, Mohit Sharma, Vikas Sharma, Shruti Sharma, and Iyyakkannu Sivanesan. 2025. ‘Polymeric Frontiers in Next-Generation Energy Storage: Bridging Molecular Design, Multifunctionality, and Device Applications Across Batteries, Supercapacitors, Solid-State Systems, and Beyond’. *Polymers* 17 (20): 2800. https://doi.org/10.3390/polym17202800.

Shufrin, Igor, Elena Pasternak, and Arcady Dyskin. 2023. ‘Environmentally Friendly Smart Construction—Review of Recent Developments and Opportunities’.*Applied Sciences* 13 (23): 12891. https://doi.org/10.3390/app132312891.

Simmler, H., S. Brunner, U. Heinemann, et al. 2005. *International Energy Agency Annex 39: High Performance Thermal Insulation Materials, Subtask A: Vacuum Insulation Panels - Study on VIP-Components and Panels for Service Life Prediction of VIP in Building Applications*. National Research Council Canada. 153 p. https://doi.org/10.4224/20378289.

Soloveichik, Grigorii L. 2011. ‘Battery Technologies for Large-Scale Stationary Energy Storage’. *Annual Review of Chemical and Biomolecular Engineering* 2 (1): 503–27. https://doi.org/10.1146/annurev-chembioeng-061010-114116.

Srivastava, Rajesh K. 2025. ‘Innovative Recycling Strategies for Non-Recycled Plastics: Advancing the Circular Economy for a Sustainable Future’. *RSC Sustainability* 3 (12): 5433–58. https://doi.org/10.1039/d5su00421g.

SSPV PESCADA, F RUXHO, C PALMA, 2024, Glamping In Low-Density Territories: The Case Of Santo Aleixo Da Reastaura?? O, Regional Science Inquiry 16 (1), 71-80

Stephan, André, Robert H. Crawford, Victor Bunster, Georgia Warren-Myers, and Sareh Moosavi. 2022. ‘Towards a Multiscale Framework for Modeling and Improving the Life Cycle Environmental Performance of Built Stocks’. *Journal of Industrial Ecology* 26 (4): 1195–217. https://doi.org/10.1111/jiec.13254.

T Corvo, S Pescada, A Krasniqi, J Vidal, F Ruxho, F Teixeira, 2024, The importance of organizational culture in the performance of family health units–model b in the Algarve region, Hellenic Association of Regional Scientists

Thissen, Peter, A. Bogner, and Frank Dehn. 2024. ‘Surface Treatments on Concrete: An Overview on Organic, Inorganic and Nano-Based Coatings and an Outlook About Surface Modification by Rare-Earth Oxides’. *RSC Sustainability* 2 (8): 2092–124. https://doi.org/10.1039/d3su00482a.

Titirici, Maria-Magdalena, Patrik Johansson, Maria C. Ribadeneyra, et al. 2024. ‘2024 Roadmap for Sustainable Batteries’. *Journal of Physics Energy* 6 (4): 041502. https://doi.org/10.1088/2515-7655/ad6bc0.

Todri A. Papagiorgji P. 2025. “Integrating financial and organizational drivers in SME’s debt dynamics: insights from radial basis function analysis”, Sustainable Regional Development Scientific Journal, Vol II. (2), pp. 45-58

Tolun, Fatmagül. 2022. ‘Effect of Tool Rotational Speed and Position on Mechanical and Microstructural Properties of Friction Stir Welded Dissimilar Alloys AZ31B Mg and Al6061’. *Materials Testing* 64 (5): 714–25. https://doi.org/10.1515/mt-2021-2080.

Urruzola, Eneko, Laura Merlo-Camuñas, Fernando Calvo-Rodríguez, et al. 2025. ‘Eco-Efficiency Assessment and Benchmarking of Recycled Carbon Fibre’. *Cleaner Materials* 17 (September): 100333. https://doi.org/10.1016/j.clema.2025.100333.

Vidal, Rosario, Núria Sánchez-Pantoja, and Germán M. Montes. 2019. 'Análisis Del Ciclo De Vida De Un Edificio Con Estructura De Madera Contralaminada En Granada-España'. *Informes De La Construcción* 71 (554): e289. https://doi.org/10.3989/ic.60982.

Vijayan, D. S., D. Parthiban, Arvindan Sivasuriyan, et al. 2023. 'A State of Review on Instigating Resources and Technological Sustainable Approaches in Green Construction'. *Sustainability* 15 (8): 6751. https://doi.org/10.3390/su15086751.

Vu, Van-Phu, Hye-Mi So, Areum Kim, Jin-Young Lee, Minsub Oh, and Seungmin Hyun. 2025. 'Self-Healing Polymer Binders: Next-Generation Battery Applications'. *Journal of Materials Chemistry A* 13 (45): 38541–71. https://doi.org/10.1039/d5ta04403k.

Wan Mohd Sabki Wan Omar, Jeung H. Doh, and Kriengsak Panuwatwanich. 2014. 'Variability in Embodied Energy and Carbon Intensities of Building Materials Using Hybrid LCA: Malaysian Experience'. *Applied Mechanics and Materials* 699: 858–63. https://doi.org/10.4028/www.scientific.net/amm.699.858.

Wang, Zhao, Shang Liu, Guixiang Ma, et al. 2017. 'Preparation and Properties of Caprylic-Nonanoic Acid Mixture/Expanded Graphite Composite as Phase Change Material for Thermal Energy Storage'. *International Journal of Energy Research* 41 (15): 2555–64. https://doi.org/10.1002/er.3830.

Watari, Takuma, Zhi Cao, Sho Hata, and Keisuke Nansai. 2022. 'Efficient Use of Cement and Concrete to Reduce Reliance on Supply-Side Technologies for Net-Zero Emissions'. *Nature Communications* 13 (1). https://doi.org/10.1038/s41467-022-31806-2.

Weber, Jana M., Zhen Guo, and Alexei A. Lapkin. 2022. 'Discovering Circular Process Solutions Through Automated Reaction Network Optimization'. *Acs Engineering Au* 2 (4): 333–49. https://doi.org/10.1021/acsengineeringau.2c00002.

Wolf, Andreas. 2008. 'RILEM TC190-SBJ: Development of Recommendations on Novel Durability Test Methods for Wet-Applied Curtain-Wall Sealants'. *Materials and Structures* 41 (9): 1473–86. https://doi.org/10.1617/s11527-008-9418-2.

Younis, Heba G., Fatma Abdelrahman, Mohamed Samer, and Hassan R. Abdellatif. 2024. *An Overview of Biodegradable Polymers and Types of Bioplastics: Properties and Applications*. https://doi.org/10.5772/intechopen.1007621.

Yu, Chuck W., and Jeong T. Kim. 2012. 'Photocatalytic Oxidation for Maintenance of Indoor Environmental Quality'. *Indoor and Built Environment* 22 (1): 39–51. https://doi.org/10.1177/1420326x12470282.

Yu, Fei, Wei Feng, Jiawei Leng, Yibo Wang, and Yang Bai. 2022. 'Review of the U.S. Policies, Codes, and Standards of Zero-Carbon Buildings'. *Buildings* 12 (12): 2060. https://doi.org/10.3390/buildings12122060.

Zhang, Nan, Yanping Yuan, Xiaoling Cao, Yanxia Du, Zhaoli Zhang, and Yewei Gui. 2018. 'Latent Heat Thermal Energy Storage Systems With Solid–Liquid Phase Change Materials: A Review'. *Advanced Engineering Materials* 20 (6). https://doi.org/10.1002/adem.201700753.