frontiers | Frontiers in Sustainable Cities

TYPE Review
PUBLISHED 22 May 2025
DOI 10.3389/frsc.2025.1569362

Check for updates

OPEN ACCESS

EDITED BY
Ka Leung Lok,
University of South Wales, United Kingdom

REVIEWED BY
Edmund Zolnik,
George Mason University, United States
Ivan Fung,
The University of Hong Kong,
Hong Kong SAR, China

*CORRESPONDENCE
Williams Chibueze Munonye
✉ wilmu439@student.liu.se;
✉ williamsmunonye@gmail.com

RECEIVED 21 February 2025
ACCEPTED 05 May 2025
PUBLISHED 22 May 2025

CITATION
Munonye WC and Ajonye GO (2025) Energy-driven circular design in the built environment: rethinking architecture and infrastructure.
Front. Sustain. Cities 7:1569362.
doi: 10.3389/frsc.2025.1569362

Energy-driven circular design in the built environment: rethinking architecture and infrastructure

Williams Chibueze Munonye[1]* and George Oche Ajonye[2]

[1]Department of Thematic Studies, Linkoping University, Linkoping, Sweden, [2]Department of Media and Technology, Linkoping University, Linkoping, Sweden

This study explores the integration of energy-driven circular design principles within the built environment, aiming to foster sustainable, low-carbon cities and buildings. Currently as urbanization accelerates and environmental concerns heighten, the need for circular economy practices that promote energy efficiency, resource optimization, and waste reduction becomes increasingly urgent. However, through exploring existing literature, the study identifies the importance of energy-efficient systems and circular design, highlighting innovative approaches such as renewable energy integration, adaptive reuse of materials, and building energy optimization. This paper also examines the barriers to widespread adoption of these principles, including technological, economic, and policy-related challenges. Through a multi-disciplinary perspective, this study proposes actionable strategies for overcoming these barriers, emphasizing the importance of collaboration between architects, engineers, policymakers, and industry stakeholders. The paper also discusses the role of digital tools, such as Building Information Modeling (BIM), in enhancing the implementation of circular economy practices in construction and renovation. In conclusion, the study reinforces the potential of energy-driven circular design to significantly reduce the environmental impact of the built environment, offering pathways to achieving climate resilience and sustainability goals in urban contexts.

KEYWORDS

energy-driven design, green architecture, circular economy, sustainable cities, building energy optimization, renewable energy, urban sustainability

1 Introduction to energy-driven circular design in the built environment

The built environment plays a pivotal role in addressing global sustainability challenges, notably resource depletion, energy overconsumption, and waste generation (Azar and Menassa, 2014; Bocken et al., 2016; Sachs, 2015; Abanda et al., 2021). As environmental degradation intensifies, the convergence of energy efficiency and circular design principles is increasingly recognized as essential for sustainable urban development. This paradigm shift seeks to minimize waste, optimize resource use, and reduce carbon emissions across the entire building lifecycle from design and construction to operation and end-of-life processes (Blomsma and Brennan, 2017; Horne, 2017; Goulden et al., 2017).

Circularity, in this context, represents a regenerative design philosophy that maintains the value of materials and resources within the economy through reuse, refurbishment, remanufacturing, and recycling. It counters the dominant linear model of “take-make-dispose” by fostering closed-loop systems that emphasize longevity and adaptability (Adams, 2016; Blomsma and Brennan, 2017).

An illustrative example of this approach is Park 20|20 in the Netherlands, the first full-service Cradle-to-Cradle-inspired office park. By employing modular construction methods, renewable energy integration, and material circularity, Park 20|20 demonstrates how circular design can intersect with energy efficiency to achieve nearly net-zero emissions and scalable sustainability.

As urbanization accelerates, the built environment which includes residential, commercial, infrastructural, and transportation systems accounts for a significant portion of global energy use and waste production (Bocken et al., 2016; Horne, 2017; Brás et al., 2019). Energy-driven circular design offers a transformative response, merging technological innovation with ecological responsibility to create buildings and infrastructures that are not only energy-efficient but also materially regenerative (Azar and Menassa, 2014; Chenari et al., 2021; Chen et al., 2021).

At its foundation, energy-driven circular design emphasizes energy efficiency, aiming to reduce buildings' operational energy demands while ensuring occupant comfort, health, and well-being (Ahmadi et al., 2020; Himeur et al., 2020). This entails the use of high-performance insulation, smart windows, and building systems that optimize energy consumption through real-time environmental data and adaptive technologies (Bell et al., 2022; Cirella et al., 2021). Advanced solutions such as sensors, automated energy management systems, and predictive analytics allow buildings to self-regulate based on occupancy and climatic variations, thus reducing carbon footprints and operational costs (Frosch and Gallopoulos, 1989; De Jesus and Mendonça, 2018; Farzaneh et al., 2021).

Renewable energy systems are integral to this model. Solar, wind, and geothermal technologies enable buildings to generate clean energy, often reaching net-zero or even positive energy standards (Jones et al., 2019; Chenari et al., 2021). Coupled with energy storage solutions and smart grids, these systems allow for the efficient redistribution and temporal balancing of energy demands, enhancing grid resilience and local energy autonomy (Lee et al., 2022; Kotsopoulos, 2022).

However, the circularity dimension extends beyond energy. It incorporates environmental, economic, and social considerations, prioritizing long-term durability, material reuse, and life-cycle value (Bocken et al., 2016; Hauge et al., 2011; Gillott et al., 2023). Design strategies include modular construction, disassemblable components, and locally sourced, low-impact materials to minimize environmental footprints and maximize resource efficiency (McDonough and Braungart, 2002; Parker et al., 2021; Lin and Chen, 2022). These methods shift construction from a disposable model toward a regenerative, adaptive one.

Crucially, energy-driven circular design emphasizes closing the energy loop sharing, storing, and reusing energy across building networks. District heating and cooling systems decentralized renewable generation, and energy-sharing microgrids exemplify how localized solutions can meet broader sustainability goals (Wang et al., 2017; Gillott et al., 2023; Van Ewijk et al., 2023). These systems reduce transmission losses, enhance reliability, and foster community resilience in the face of climate and energy crises (Sebestyén, 2021; Olatunde et al., 2024).

This integrative design philosophy envisions smart, regenerative, and self-sustaining urban systems, where buildings not only consume but also produce, manage, and redistribute energy and materials. It calls for interdisciplinary collaboration, spanning architecture, engineering, urban planning, and policy, to scale innovations and overcome implementation barriers (Rajput and Singh, 2019; Ntasiou and Andreou, 2017; Nisar et al., 2024).

However, the integration of energy efficiency and circular design within the built environment has been a prominent area of research in recent years. However, despite significant advances in both fields, substantial gaps remain in understanding how to effectively merge these concepts in real-world applications at scale. The current status quo in literature primarily focuses on two parallel but often disconnected streams of research: energy efficiency in building design and circular economy in materials management.

While energy-efficient buildings and energy management systems have been studied extensively (Azar and Menassa, 2014; Horne, 2017; Chen et al., 2021), most research has concentrated on operational energy demand reduction through technological innovations like smart grids and adaptive systems (Bell et al., 2022; Cirella et al., 2021). These studies predominantly focus on building energy performance, often isolated from the lifecycle implications of material usage and waste management. However, the operational success of energy efficiency systems is limited if the broader environmental impacts of construction, material lifecycle, and waste management are not simultaneously addressed.

On the other hand, research in circular economy has emphasized material reuse, recycling, and design for disassembly (McDonough and Braungart, 2002; Parker et al., 2021). Circular design strategies often focus on the minimization of construction waste, the durability of materials, and the transition to regenerative systems. However, the integration of energy systems within circular models remains underexplored. There is a lack of studies that systematically examine how energy-driven circularity can be applied to both the operation of buildings and their material reuse, particularly in the context of reducing carbon footprints and contributing to net-zero goals.

Recent literature suggests that energy-driven circular design has the potential to bridge these two domains. This concept, however, remains in its nascent stages, with few comprehensive models that combine energy efficiency, renewable energy integration, and circular material practices into cohesive, scalable building designs. A major gap lies in the absence of frameworks that facilitate the simultaneous optimization of energy and materials throughout a building's lifecycle (Hauge et al., 2011; Gillott et al., 2023; Kharbouch et al., 2017). Furthermore, existing models typically focus on individual technologies or design strategies without addressing how these can be integrated into broader, more sustainable urban systems.

This work addresses these gaps by proposing a comprehensive approach to energy-driven circular design. Through merging principles of circular economy and energy efficiency, this study explores the synergies between material and energy flow within building systems and urban infrastructures. Specifically, it investigates how renewable energy systems, energy-sharing networks, and modular construction can be combined to create regenerative urban environments. The research proposes new frameworks for integrating life-cycle energy analysis with circular design principles, enabling a holistic approach to sustainability in the built environment.

Moreover, the study moves beyond isolated case studies or technical innovations to address scalability and equity. It engages with geographic and socio-economic contexts, acknowledging that the barriers to implementation differ widely between developed and developing regions. This aspect is critical for ensuring that energy-driven circular designs are not only technically feasible but also accessible to a broader range of urban communities, including those in resource-constrained environments.

In essence, energy-driven circular design is a regenerative, systems-oriented framework that integrates energy efficiency, renewable energy, and material circularity. Through capitalizing on technological innovations, ecological materials, and adaptive urban infrastructure, this approach minimizes environmental impact while enhancing urban resilience and economic sustainability. The buildings and cities of the future, underpinned by this vision, will not only consume less but actively contribute to their surroundings generating, sharing, and recycling energy and materials to create a more livable, equitable, and climate-resilient world (Rajput and Singh, 2019; Yu et al., 2024; Shree et al., 2025).

Ultimately, energy-driven circular design presents a forward-looking strategy for rethinking architecture and infrastructure, fostering sustainability at every stage of the building lifecycle (Jones et al., 2019; Yu et al., 2024; Bayat and Kashani, 2025) (see Figure 1).

2 Methodology

This article adopts a narrative review methodology to critically explore the intersections of energy efficiency and circular economy principles within the built environment, with a particular focus on architecture and infrastructure. The narrative approach was selected for its flexibility in synthesizing diverse bodies of literature and contextual case studies to generate conceptual clarity, identify research gaps, and offer a forward-looking perspective (Greenhalgh et al., 2018).

The research process involved a qualitative synthesis of academic literature and real-world case studies from peer-reviewed journals, institutional reports, and practitioner sources. Literature was identified through systematic searches across key academic databases including Scopus, Web of Science, ScienceDirect, and Google Scholar. Search terms included combinations of: *"energy-efficient architecture," "circular design in construction," "built environment and sustainability," "modular buildings," "net-zero energy buildings," "infrastructure circularity,"* and *"renewable energy in architecture."* The search was limited to English-language publications from 2009 to 2025 to capture both foundational and contemporary developments in the field.

To ensure conceptual breadth and empirical grounding, the synthesis incorporated seminal works on circular economy and architectural sustainability (e.g., (McDonough and Braungart, 2002; Blomsma and Brennan, 2017), as well as case-based literature that illustrated the application of energy-driven circular design principles in practice (e.g., Park 20|20 in the Netherlands, BedZED in the UK). Case studies were selected for their geographical diversity, documented performance outcomes, and relevance to energy-material integration in design.

Rather than following a rigid coding or meta-analytic framework, the narrative method enabled a thematic synthesis, allowing insights to emerge inductively around design strategies, technological innovations, implementation challenges, and policy implications. This approach is particularly suited to emerging interdisciplinary topics, such as energy-driven circularity, where evidence is heterogeneous and spread across disciplines.

Overall, this methodology allowed for a holistic, systems-oriented understanding of how energy and circularity can be meaningfully integrated into the design, construction, and operation of buildings and infrastructure (see Figures 2, 3).

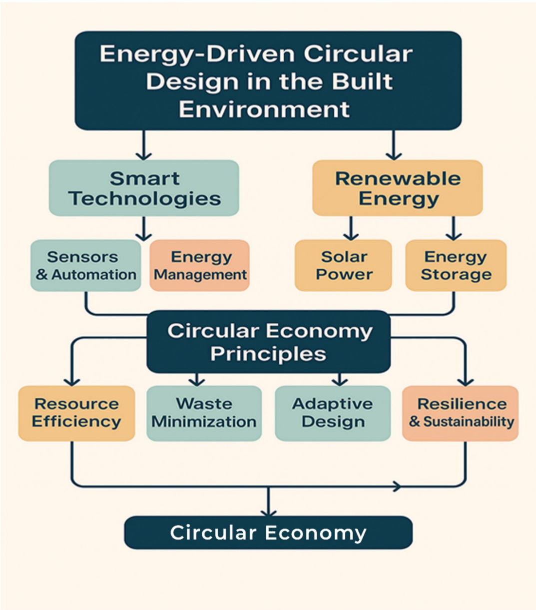

FIGURE 1
The flowchart intricately maps the interconnected components of energy-driven circular design in the built environment, illustrating how architecture, infrastructure, and energy systems must converge for sustainability, beginning with intelligent material selection that minimizes waste, modular construction that ensures adaptability, and renewable energy integration that reduces reliance on fossil fuels while fostering resilience. Advanced technologies such as AI-driven energy management, IoT-enabled monitoring, and Building Information Modeling (BIM) optimize efficiency across a building's lifecycle, reinforcing circularity by enabling real-time adaptation to energy demands. Waste-to-energy systems, green infrastructure, and district-level energy sharing complete the cycle, proving that sustainability is not just about resource efficiency but about creating regenerative urban systems. The model insists that design must be dynamic, responsive, and ecosystem-integrated, synchronizing with climate imperatives while ensuring long-term viability in an evolving environmental landscape. Source: Developed by the Authors.

3 The role of architecture and infrastructure in sustainable development

At the heart of energy-driven sustainable design lies the circular economy (CE). CE frameworks reject the 'take-make-waste' model, instead proposing regenerative cycles of material use and reuse (McDonough and Braungart, 2002; Adams, 2016). In architecture, this translates into cradle-to-cradle design, where components are selected for durability, separability, and recyclability (Sebestyén, 2021; Rios et al., 2022). The goal is not merely to build but to build with foresight anticipating disassembly, reuse, and future performance.

Material innovation plays a pivotal role. The use of reclaimed steel, recycled concrete, and bio-based composites supports a circular construction sector (Chenari et al., 2021; Williams et al., 2023). Industrial symbiosis extends this logic by repurposing industrial by-products across sectors, thereby reducing raw material dependency and embedded carbon (Ntasiou and Andreou, 2017; Cristino et al., 2021).

FIGURE 2
Native review methodology adopted by the authors. Source: Developed by the Authors.

FIGURE 3
Image presents a structured, color-coded conceptual framework linking six key sections of the article, guiding readers through ideas from introduction to outlook. Source: Developed by the Authors.

Moreover, the built environment is foundational to achieving the United Nations Sustainable Development Goals (SDGs), with several of these goals directly linked to architecture and infrastructure. SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 12 (Responsible Consumption and Production) highlight the importance of integrating energy-efficient systems, circular economy principles, and sustainable design into infrastructure. Architecture and infrastructure must evolve in tandem with these goals, focusing on reducing energy consumption, enhancing resource efficiency, and facilitating communities' transitions to low-carbon, resilient futures (Sachs, 2015; Rios et al., 2022; Parker et al., 2021; Nisar et al., 2024). Nowadays, global populations increase, and urbanization expands, the impact of the built environment on sustainability becomes increasingly significant, urging the need for innovations in construction, energy management, and urban planning (Mavakala et al., 2017; Mahmood et al., 2022; Lu et al., 2020).

Architectural design, historically centered on aesthetic appeal and functional utility, now faces the dual challenge of addressing environmental considerations while meeting the needs of growing populations (Mahmood et al., 2022; Ruparathna et al., 2016; Liu and Wu, 2022; Hensen and Lamberts, 2011). With the emergence of sustainability imperatives, architects are redefining their approaches to design. Circular economy principles stress the importance of buildings and infrastructure that not only respond to environmental challenges but also integrate adaptability to evolving societal needs (Lieder and Rashid, 2016; Kibert and Fard, 2012; Jones et al., 2019). This involves designing structures with flexibility, modularity, and the capacity for future repurposing, reducing waste, and improving sustainability over time (Horne, 2017; Hobson et al., 2020). Moreover, energy-efficient systems embedded in infrastructure are pivotal in ensuring long-term sustainability. The ongoing integration of low-carbon technologies and sustainable design principles is crucial to achieving the SDGs in urban areas and beyond (Bocken et al., 2016; Geissdoerfer et al., 2017).

Energy-efficient systems are integral to the development of sustainable cities and communities. These systems span multiple sectors of urban infrastructure, including transportation, water management, and waste management. Each of these sectors plays a critical role in creating energy-efficient and sustainable urban environments. Transportation, for instance, is a significant contributor to carbon emissions (Kumar and Cao, 2021; Jones et al., 2019; Himeur et al., 2021). The shift towards energy-efficient systems such as electric vehicles (EVs), public transport networks powered by renewable energy, and integrated smart traffic management helps reduce the carbon footprint of cities. Smart traffic management systems can significantly decrease energy consumption by optimizing traffic flow, reducing congestion, and enabling real-time data collection to adjust system performance (Geissdoerfer et al., 2017; Lin and Chen, 2022; Nisar et al., 2024). Similarly, high-speed rail networks, powered by renewable sources such as solar and wind, represent a forward-thinking approach to sustainable public transport infrastructure (Parker et al., 2021; Mahmood et al., 2022). These systems not only enhance mobility but also align with broader sustainability goals by reducing dependence on fossil fuels and decreasing greenhouse gas emissions. In reflection, buildings, responsible for over 30% of global energy consumption, are key intervention points. Energy-efficient buildings integrate technologies such as solar panels, LED lighting, passive ventilation, and smart thermostats to reduce operational emissions (Sun et al., 2021; Rios et al., 2022). Passive strategies shading, orientation, thermal mass demonstrate that intelligent design can outperform even high-tech retrofits when it comes to energy savings (Ürge-Vorsatz et al., 2020). Studies affirm that these buildings contribute not only to climate goals but also to economic savings and improved occupant wellbeing (Hauge et al., 2011; Olatunde et al., 2024).

Furthermore, integrating renewable energy sources such as solar, wind, or geothermal into urban infrastructure helps reduce reliance on non-renewable energy sources, thus contributing to SDG 7. For instance, the incorporation of solar panels in urban infrastructure ranging from individual buildings to entire districts creates a renewable energy ecosystem that decreases the strain on conventional power grids (Ruparathna et al., 2016). Geothermal heating and cooling systems, when appropriately harnessed, can also provide a sustainable solution for temperature regulation in buildings, especially in colder climates (Azar and Menassa, 2014; Nisar et al., 2024; Ruparathna et al., 2016).

Energy-efficient buildings powered by renewable energy are also vital in reducing urban energy consumption. These buildings utilize advanced energy-saving technologies such as solar panels, energy-efficient lighting, and smart thermostats to minimize their carbon footprint (Kibert and Fard, 2012; Rios et al., 2022; Sun et al., 2021). Moreover, passive design strategies such as orientation, shading, and natural ventilation are essential to reducing the need for mechanical heating and cooling (Sun et al., 2021; Ürge-Vorsatz et al., 2020; Olatunde et al., 2024). Integrating passive design elements such as natural ventilation, thermal mass, and solar orientation can reduce building energy demand by 30–70%, particularly in residential and mid-rise commercial buildings (Wang et al., 2017; Hauge et al., 2011). Studies across European and Asian cities demonstrate that, at both building and district scales, such strategies significantly lower heating and cooling loads, contributing to urban energy efficiency (Olatunde et al., 2024; Mao and Cao, 2025; Shree et al., 2025; Tonellato et al., 2025). Collectively, these interventions support the transition to low-carbon cities, aligning with SDG 11's goal of sustainable urban development.

The emergence of zero-energy buildings (ZEBs) is a significant milestone in energy-efficient building design. ZEBs are designed to produce as much energy as they consume through a combination of energy-efficient construction practices and the integration of on-site renewable energy production, such as solar panels and wind turbines (Ahmadi et al., 2020; Olatunde et al., 2024; Wags and Ifeanyi, 2024). These buildings represent a breakthrough in reducing both the operational energy demands of buildings and their overall environmental impact. Zero-energy buildings are a response to the growing need for sustainable housing solutions, especially as urban populations increase and the demand for energy-intensive buildings rises. The success of these buildings depends not only on the integration of efficient energy systems but also on innovative construction materials and technologies that further enhance their sustainability (Lin and Chen, 2022; Williams et al., 2023; Yu et al., 2024).

More importantly, the circular economy (CE) is a concept that focuses on the continual reuse of resources, eliminating waste and promoting sustainability in the built environment (Vink and Vinke-de Kruijf, 2024; Olatunde et al., 2024; Sachs, 2015). Circular economy principles applied to architectural design emphasize the need to create buildings and infrastructure that are not only resource-efficient but also adaptable and resilient to environmental changes (Sebestyén, 2021; Rios et al., 2022; Van Ewijk et al., 2023). A key element of CE in architecture is the idea of "cradle-to-cradle" design, in which materials are reused or recycled rather than discarded after their useful life (McDonough and Braungart, 2002; Adams, 2016; Abanda et al., 2021). This approach contrasts sharply with the traditional "cradle-to-grave" model, which promotes linear consumption and waste generation.

Incorporating circular economy principles into architectural design involves rethinking how buildings are constructed, maintained, and eventually deconstructed. Materials selection is an essential component, as architects and designers aim to use resources that are durable, recyclable, and non-toxic (Bell et al., 2022; Azar and Menassa, 2014; Williams et al., 2023). Additionally, the design of buildings that can be easily disassembled or repurposed at the end of their lifecycle helps minimize waste and maximize resource reuse (Blomsma and Brennan, 2017; Chenari et al., 2021). This approach reduces the environmental footprint of buildings by ensuring that materials can be efficiently returned to the supply chain, reducing the need for new resources and lowering the overall carbon footprint of construction projects (Rios et al., 2022).

The role of industrial symbiosis within circular economy frameworks is also evident in the built environment. Through utilizing the waste products of one industry as inputs for another, industrial symbiosis reduces material waste and promotes resource efficiency (Ntasiou and Andreou, 2017; Cristino et al., 2021). In the context of architecture and infrastructure, this can involve the reuse of construction materials, such as recycled steel, reclaimed wood, and repurposed concrete, in new buildings and infrastructure projects. The integration of these materials not only supports the reduction of resource extraction but also contributes to the environmental sustainability of construction practices.

Beyond materials, circular economy principles extend to the operational aspects of buildings, focusing on energy, water, and waste management. For example, water recycling systems, such as rainwater harvesting and greywater reuse, help reduce the demand for freshwater, which is a finite resource in many urban areas (Huang et al., 2022; Chen et al., 2021; Habibi and Kahe, 2024). Similarly, smart waste management technologies that optimize collection, sorting, and recycling help reduce the amount of waste sent to landfills, supporting the circular economy model. The integration of these technologies into urban infrastructure helps cities become more sustainable, resilient, and capable of supporting growing populations without compromising environmental quality.

Nowadays, smart buildings represent another frontier in the intersection of architecture, energy efficiency, and sustainability. These buildings integrate advanced technologies, such as Internet of Things (IoT) devices, sensors, and machine learning algorithms, to optimize energy use, improve occupant comfort, and reduce environmental impacts (Himeur et al., 2021; Gillott et al., 2023; Farzaneh et al., 2021). For example, smart HVAC (heating, ventilation, and air conditioning) systems can adjust their operations based on real-time data, optimizing energy use and reducing wasted energy (Hobson et al., 2020). Similarly, occupancy sensors can detect when spaces are unoccupied, allowing for the automatic adjustment of lighting and temperature settings, further enhancing energy efficiency. The rise of artificial intelligence (AI) and machine learning in building management systems is also transforming how energy is consumed in the built environment (Gillott et al., 2023; Himeur et al., 2021; Elshafei et al., 2022). AI algorithms can analyze vast amounts of data to predict energy consumption patterns, optimize building performance, and reduce energy waste (Farzaneh et al., 2021; Williams et al., 2023). These systems offer an unprecedented level of control over building operations, enabling the creation of truly sustainable and energy-efficient buildings. The integration of circular economy principles, energy-efficient technologies, and smart systems into architecture and infrastructure plays a pivotal role in shaping sustainable urban environments.

4 Design strategies for energy-driven circular architecture

Energy-driven circular architecture represents a holistic approach to sustainable building design, combining the principles of circular economy with energy efficiency. In the context of architecture, circularity refers to creating buildings that are designed with the entire lifecycle in mind, aiming for resource efficiency, waste reduction, and energy optimization (Lieder and Rashid, 2016; Hensen and Lamberts, 2011; Sachs, 2015). The integration of energy-efficient systems, renewable energy sources, and the consideration of long-term material reuse play pivotal roles in reducing the environmental footprint of buildings (Hauge et al., 2011; Himeur et al., 2021; Huang et al., 2022; Lee et al., 2022). To achieve these goals, several strategies can be employed, which are outlined below.

Circular design strategies in the built environment emphasize the long-term reduction of resource consumption, maximization of energy efficiency, and minimization of waste. These strategies play a central role in transforming traditional buildings into energy-driven, sustainable structures. The following approaches outline key strategies for integrating circular principles in building design:

4.1 Life cycle and economic feasibility analysis in energy-driven circular architecture

Energy-driven circular architecture demands a profound understanding of environmental and economic trade-offs over the entire life span of a building. Life Cycle Analysis (LCA) and Life Cycle Costing (LCC) provide foundational methodologies to assess the cumulative environmental and financial performance of architectural solutions. These frameworks support decision-making by quantifying the environmental impacts such as greenhouse gas emissions and resource depletion and evaluating economic feasibility through cost–benefit analyses, return on investment (ROI), and potential policy incentives.

LCA offers a systematic method for assessing the environmental burden of building materials and systems from cradle to cradle, encompassing extraction, processing, manufacturing, construction, use, and end-of-life stages (McDonough and Braungart, 2002; Geissdoerfer et al., 2017). In energy-driven circular architecture, LCA is critical for identifying hotspots in material flows and energy consumption, enabling designers to prioritize low-impact, renewable, and reusable materials (Blomsma and Brennan, 2017; Gillott et al., 2023).

A growing body of research emphasizes the integration of LCA into Building Information Modeling (BIM), which enables scenario testing and optimization during early design phases (Abanda et al., 2021). BIM-LCA integration ensures that material choices are aligned with circular principles and energy targets, reducing embedded carbon while supporting future adaptability and dismantling. For example, Ahmadi et al. (2020) demonstrated that substituting conventional insulation with recycled cellulose in a zero-energy building reduced embodied carbon by 36% over a 50-year lifespan.

Moreover, the LCA approach supports evaluating various circular strategies such as adaptive reuse, modularity, and regenerative material loops. This shifts the architectural discourse from efficiency to effectiveness, where long-term regenerative potentials are central (McDonough and Braungart, 2002; De Jesus and Mendonça, 2018). Blomsma and Brennan (2017) argue that such framing prolongs resource productivity and fosters-built environments that serve as material banks for future generations.

LCA also encourages a temporal perspective in sustainable building design, assessing environmental benefits and burdens over time rather than focusing on immediate outcomes. This temporal dimension is vital for climate-aligned architecture, as embodied emissions often outweigh operational savings if short-term frames dominate. Thus, LCA acts not merely as an accounting tool but as a design philosophy grounded in planetary boundaries and intergenerational justice.

Therefore, LCC complements LCA by examining the total cost of ownership, including initial capital costs, operational expenses, maintenance, and end-of-life value recovery. A common barrier to adopting circular and energy-efficient strategies in building design is the perceived high upfront cost. However, Life Cycle Costing (LCC) analyses reveal that specific investments such as high-performance insulation, double-glazed windows, and passive solar design can yield long-term savings of 20–40% in operational energy costs, particularly in residential and office buildings across temperate regions like Northern Europe and North America (Doczy and AbdelRazig, 2017; Chenari et al., 2021; Abedi et al., 2025; Jaffar Abass and Muthulingam, 2025).

For instance, Chen et al. (2021) found that buildings incorporating smart ventilation and thermal optimization systems reduced operational costs by up to 27% compared to traditional structures. Furthermore, Doczy and AbdelRazig (2017) applied multi-attribute utility theory (MAUT) and the analytic hierarchy process (AHP) to evaluate green building scenarios. Their analysis revealed that although green design costs were initially 8–10% higher, lifecycle savings in energy and water consumption resulted in positive net present value (NPV) within 7 to 10 years.

These insights are particularly relevant in the context of dynamic urban energy systems, where demand-side flexibility and distributed renewables are becoming mainstream (Abanda et al., 2021; Farzaneh et al., 2021). Life cycle cost analysis allows architects and policymakers to frame investments not as sunk costs but as resilient infrastructure enabling long-term socio-technical and ecological dividends (Cirella et al., 2021).

Additionally, LCC enables the visualization of feedback loops between circular design and long-term resource autonomy. When buildings are treated as evolving material stockpiles with deconstruction, reuse, and refurbishment planned from the outset life cycle costs decline as materials retain financial value across multiple life cycles. This fosters a transition from a 'linear depreciation model' of assets to a regenerative value retention paradigm, resonating with circular economy theory.

Incentive structures, including tax credits, green building certifications, feed-in tariffs, and performance-based subsidies, significantly improve the economic feasibility of circular and energy-efficient building solutions. For example, Bell et al. (2022) noted that climate adaptation strategies integrated into HVAC systems under future climate scenarios became financially viable only when coupled with regional energy-efficiency subsidies.

Moreover, market-based mechanisms and green finance instruments such as energy performance contracts (EPCs), on-bill financing, and green bonds are essential in scaling circular architecture in the private sector. Jones et al. (2019) emphasize the role of collective agency and institutional innovation in legitimizing green building markets. Through collaborative models involving architects, financial institutions, and regulators, cost premiums for energy-driven circular buildings can be offset via lifecycle-based procurement and long-term public-private partnerships.

However, the true value of integrating LCA and LCC lies in enabling systemic design trade-offs that balance environmental performance with economic return. Elshafei et al. (2022) recommend using AHP as a decision-support tool to simultaneously optimize environmental, social, and financial criteria. By quantifying design alternatives through multi-criteria models, stakeholders can prioritize interventions that align with the triple bottom line planet, people, and profit.

Gillott et al. (2023) proposed the "Regenerate" tool for assessing circularity in existing buildings, which includes lifecycle performance indicators for both materials and energy. Their work offers a practical pathway to apply life cycle thinking in both new construction and retrofitting. Similarly, Habibi and Kahe (2024) demonstrated that green infrastructure, such as urban greenery and reflective surfaces, not only improves microclimates but reduces cooling loads and related operating costs, creating economic-environmental synergies.

Critically, synthesizing LCA and LCC also requires a shift toward systems thinking. Architecture must be approached not merely as static form but as dynamic infrastructure within socio-ecological systems. This lens enables planners to anticipate interdependencies between building materials, energy flows, user behaviors, and policy constraints so that design becomes anticipatory rather than reactive. Systems thinking expands lifecycle evaluation beyond a technical assessment into a platform for governance, resilience, and innovation.

Despite its benefits, implementing LCA-LCC frameworks at scale faces significant challenges, including data fragmentation, modeling uncertainty, and institutional inertia. As Cristino et al. (2021) outline, barriers to adopting energy-saving technologies are often not technical but socio-economic, involving stakeholder resistance, lack of regulatory alignment, and insufficient performance metrics.

Addressing these gaps requires embedding life cycle approaches in regulatory frameworks, mandating material passports, and harmonizing LCA-LCC standards across regions. Moreover, the development of dynamic, AI-powered decision-support tools can enhance the granularity and responsiveness of economic and environmental evaluations (Farzaneh et al., 2021; Himeur et al., 2020).

4.2 Modular design and prefabrication

Modular design, which involves constructing buildings using pre-manufactured components, is a cornerstone of energy-driven circular architecture. This approach enables the reuse of materials and components, significantly reducing the environmental impact of construction (Jones et al., 2019; Lee et al., 2022). Modular buildings not only promote energy efficiency but also provide flexibility for future modifications, as components can be disassembled, reconfigured, and reused, thereby extending the lifecycle of materials (Bocken et al., 2016; Horne, 2017; Huang et al., 2022).

From a business model perspective, modular design fosters a circular economy by enabling manufacturers to reclaim and refurbish building components. Companies such as BoKlok and Katerra have demonstrated the viability of this approach by implementing closed-loop supply chains where modular components are designed for easy disassembly and reuse. The transition toward modularity in construction aligns with circular business models, including product-as-a-service and leasing models where customers do not own building materials outright but instead lease them, ensuring continuous material circulation (Blomsma and Brennan, 2017).

Technology integration further enhances modular construction efficiency. Building Information Modeling (BIM) and Digital Twin technologies optimize the design, manufacturing, and tracking of modular components, reducing errors and waste. Studies show that BIM integration can reduce material wastage by up to 30% while enhancing construction precision (Abanda et al., 2021). Prefabrication further reduces waste by shifting construction to controlled factory environments, which allows precise material usage and minimizes on-site disruptions (Wags and Ifeanyi, 2024). Additionally, automation in prefabrication particularly robotic assembly of wall panels and structural components has been shown to improve production efficiency by up to 30% and reduce material waste by 25–40%, especially in modular residential and commercial construction (Azar and Menassa, 2014; Bayat and Kashani, 2025; Brás et al., 2019).

Policy frameworks supporting modular construction are crucial for its adoption. Governments in Europe and North America have started to incentivize modular construction through green building certifications and financial incentives for circular design adoption (Lieder and Rashid, 2016). For instance, policies mandating material passports, which document the lifecycle and potential reuse of building materials, can enhance transparency and encourage modular adoption (Gillott et al., 2023).

4.3 Material selection and waste reduction

The selection and management of construction materials is central to energy-driven circular architecture, with implications for environmental, economic, and social sustainability. Circular design emphasizes materials that can be disassembled, reused, or recycled minimizing reliance on virgin inputs and reducing lifecycle energy demand (Frosch and Gallopoulos, 1989; Geissdoerfer et al., 2017). Empirical evidence indicates that intelligent material selection, coupled with closed-loop design strategies, significantly enhances energy efficiency and reduces embodied carbon.

One illustrative example is the *Green Lighthouse* project in Copenhagen, Denmark, which achieved 75% material reuse by integrating reclaimed wood, recycled aluminum, and modular prefabrication techniques. The building reduced its total construction waste by 54% compared to traditional models, while also achieving a 35% reduction in embodied carbon (Abanda et al., 2021; Ahmadi et al., 2020). A similar approach was used in the *BedZED eco-village* in London, where 90% of steel used was recycled, and embodied energy was cut by nearly 50% (McDonough and Braungart, 2002).

Emerging business models now facilitate circular material flows. Rotor Deconstruction in Belgium has reclaimed over 1,000 tons of materials annually, reselling them through digital platforms transforming demolition waste into marketable assets. Likewise, Salvo in the UK offers a marketplace for used construction materials, saving an estimated 30,000 tons of CO_2 per year (Adams, 2016; Blomsma and Brennan, 2017). These platforms illustrate how circular business models can scale while simultaneously addressing material scarcity and reducing the sector's carbon footprint.

Urban mining the process of extracting reusable materials from existing urban structures has gained traction as a viable circular economy strategy. A study by Rios et al. (2022) found that dismantling a high-rise building using material tagging and tracking systems enabled the recovery of over 80% of structural steel and concrete components. Technological tools such as RFID and blockchain further ensure material traceability and supply chain accountability, thereby improving the reintegration of resources into new construction cycles (Chen et al., 2021; Gillott et al., 2023).

For example, the EU-funded *Buildings as Material Banks (BAMB)* project deployed digital material passports across six pilot buildings, which enabled an average of 66% material reuse post-demolition. This approach not only preserved material value but also generated significant economic benefits, with one pilot project reporting a 22% cost saving in raw material procurement (De Jesus and Mendonça, 2018).

Additive manufacturing and 3D printing offer precise control over material usage, minimizing offcuts and construction waste. Sebestyén (2021) estimates that digital fabrication can reduce material waste by up to 60% compared to conventional construction techniques. This was validated in a 2021 pilot project in Eindhoven, Netherlands, where a 3D-printed concrete house used 30% less material and cut energy consumption in the construction phase by 40% (Farzaneh et al., 2021).

Furthermore, integrated Building Information Modelling (BIM) and simulation tools enhance design efficiency and allow for early identification of waste-intensive processes. In a comparative study of 12 commercial buildings, Azar and Menassa (2014) found that BIM-led design improved material efficiency by up to 18% and reduced operational energy use by 23%.

Policies are critical enablers of material circularity. The EU's Circular Economy Action Plan (CEAP) mandates minimum recycled content for construction materials and promotes the harmonization of deconstruction standards (De Jesus and Mendonça, 2018). Similarly, Extended Producer Responsibility (EPR) frameworks require manufacturers to design with reuse and end-of-life recovery in mind. In Germany, the Kreislaufwirtschaftsgesetz (Circular Economy Act) enforces material recovery quotas of at least 70% for non-hazardous construction and demolition waste (Geissdoerfer et al., 2017). Moreover, analytical tools such as the Analytic Hierarchy Process (AHP) and Multi-Attribute Utility Theory (MAUT) have been employed in policies framework to evaluate trade-offs between material cost, durability, and circularity. Doczy and AbdelRazig (2017) applied AHP-MAUT in a green building case study, concluding that circular materials were not only environmentally optimal but also financially competitive over a 25-year lifecycle.

Therefore, sourcing materials locally contributes to both environmental and economic sustainability. According to Mavakala et al. (2017), sourcing materials within a 500-km radius can reduce transportation emissions by up to 40%. A recent case study from Lagos, Nigeria, demonstrated that local sourcing of clay bricks and bamboo led to a 30% decrease in embodied emissions and reduced project costs by 18% (Nisar et al., 2024). This aligns with broader just transition goals, which advocate for regional resilience and equitable development pathways in the built environment.

4.4 Energy-efficient building systems

Incorporating energy-efficient building systems is fundamental to reducing energy consumption and advancing the development of net-positive energy buildings. This approach relies on a combination of passive design strategies, energy-efficient heating, cooling, and lighting systems, as well as smart technologies that optimize energy usage (Azar and Menassa, 2014; Mavakala et al., 2017; Nisar et al., 2024). Passive design strategies are particularly crucial in minimizing dependence on artificial heating and cooling, and they include key elements such as building orientation, natural ventilation, thermal mass, and insulation (Hauge et al., 2011; Mahmood et al., 2022). These features enhance the energy efficiency of buildings by utilizing natural resources like sunlight and wind to maintain optimal indoor temperatures. Properly designed passive systems reduce operational energy requirements significantly, thus leading to lower carbon footprints and improved sustainability.

In addition to passive strategies, modern energy-efficient building systems integrate advanced technologies such as energy management systems, smart meters, and automation, all of which facilitate real-time adjustments to energy consumption (Kibert and Fard, 2012; Ntasiou and Andreou, 2017; Rajput and Singh, 2019). These technologies allow for a dynamic response to changing energy demands, thereby reducing waste and improving efficiency. Smart building management systems can analyze usage patterns and automatically adjust lighting, heating, and cooling to optimize energy efficiency (Hauge et al., 2011; Mahmood et al., 2022). Additionally, IoT-enabled sensors such as smart thermostats, occupancy detectors, and CO_2 monitors are being increasingly integrated into commercial and institutional buildings, with global adoption rates rising from 8% in 2015 to over 25% by 2022 (Statista, 2023). These systems, part of broader smart building management platforms, have demonstrated energy efficiency gains of 15–30% by optimizing HVAC, lighting, and space utilization (Zhao et al., 2021; Li et al., 2020). For example, the Edge building in Amsterdam reduced its energy use intensity (EUI) by over 50% through IoT-based dynamic energy management. Such real-time data systems enable facility managers and occupants to make informed, responsive decisions that align operational performance with sustainability targets.

Energy storage solutions, including batteries and thermal storage systems, provide flexibility in managing energy generation and consumption. Such systems help buildings become more autonomous, minimizing their reliance on the grid and ensuring a consistent energy supply even during peak demand periods (Himeur et al., 2020; Rios et al., 2022; Lu et al., 2020). Advanced battery technologies, such as lithium-ion and solid-state batteries, are improving storage capacity and efficiency, making it possible for buildings to store surplus renewable energy generated during low-demand periods and use it when needed (Zaniboni and Albatici, 2022; Cirella et al., 2021). Additionally, thermal energy storage solutions, including phase change materials and chilled water storage, further enhance energy efficiency by enabling heating and cooling systems to operate more efficiently (Cristino et al., 2021; Azar and Menassa, 2014; Abanda et al., 2021).

The adoption of energy-efficient building systems also synchronizes with sustainability policies and business models that promote green architecture. Many governments and private sector stakeholders are implementing financial incentives and regulatory frameworks to encourage the adoption of these systems (Abanda et al., 2021; Hafez et al., 2023; Invidiata et al., 2018). Financial incentives such as tax credits, grants, and low-interest loans help offset the initial investment costs associated with energy-efficient technologies, making them more accessible to builders and developers. Additionally, green building certification programs such as LEED and BREEAM provide recognition for energy-efficient buildings, encouraging more widespread adoption (Hafez et al., 2023; Weinand et al., 2020).

4.5 Green infrastructure

Green infrastructure plays a pivotal role in advancing net-positive energy systems in buildings by embedding ecological functionality within the built environment. This involves the strategic incorporation of nature-based solutions such as green roofs, solar panels, and wind turbines, which empower buildings to generate their own energy, thereby reducing dependency on centralized fossil-fuel-based energy sources (Habibi and Kahe, 2024; Chatzimentor et al., 2020; Cheshmehzangi et al., 2021; Wang and Banzhaf, 2018). Green roofs deliver multifaceted environmental and social benefits, including improved insulation, stormwater management, and the mitigation of urban heat island effects. These elements not only contribute to better building performance but also enhance the livability of urban spaces through temperature regulation, noise reduction, and the introduction of habitats that support urban biodiversity (McDonough and Braungart, 2002; Chenari et al., 2021; Chen et al., 2021). Moreover, the aesthetic and psychological value of green spaces can enhance occupants' well-being and promote biophilic design principles in architecture (Chatzimentor et al., 2020; Cheshmehzangi et al., 2021).

Importantly, developers are increasingly leveraging green roofs as marketable sustainability assets, using them to substantiate claims that environmental responsibility is a guiding priority in their projects. This narrative appeals to environmentally conscious buyers and investors who perceive such features as both ethically and economically advantageous. Properties equipped with green infrastructure such as green roofs, rainwater harvesting systems, and energy-efficient HVAC have been shown to command resale premiums of 5–15%, particularly in mid-sized residential and mixed-use buildings ranging from 1,500 to 3,000 square feet in urban markets across North America and Western Europe (Aziz and Omar, 2020; Fuerst and McAllister, 2011; Mnasri et al., 2017). These properties also tend to sell faster, with reduced time on the market by an average of 10–20 days, reinforcing sustainability not just as an ecological imperative but also as a financial and branding strategy in competitive real estate sectors (Shree et al., 2025; Lamrani et al., 2021).

The integration of renewable energy sources such as solar photovoltaic systems and wind turbines further supports the transformation of buildings into self-sustaining energy hubs (Bell et al., 2022; Sathaye et al., 2011). Decentralized energy systems such as BIPV, bifacial solar panels, and vertical axis wind turbines enhance resilience and reduce emissions in high-density urban areas. In countries like Germany and Japan, government incentives covering up to 30–50% of installation costs have accelerated adoption, particularly in residential and mixed-use developments. These technologies offer high energy yields while maintaining architectural integrity and minimizing noise, making them ideal for urban integration (Weinand et al., 2020; Mao and Cao, 2025; Funcke and Bauknecht, 2016).

The energy generated by these systems can be efficiently stored through advanced storage technologies, including lithium-ion batteries, hydrogen fuel cells, and flywheel systems, thus enabling a circular energy loop that reduces waste and ensures availability during peak demand or power outages (Sachs, 2015; Sun et al., 2021). Integrating green infrastructure with smart grid systems allows buildings to optimize energy usage, sell surplus power back to the grid, or share it within local energy communities, fostering a resilient, decentralized energy economy.

These shifts are further enabled by evolving energy policies and adaptive business models that lower financial barriers and incentivize adoption. Governments worldwide are implementing targeted incentives to promote renewable technologies in construction. In Germany, the Federal Subsidy for Efficient Buildings (BEG) program offers substantial financial support for energy-efficient building projects, aiming to reduce primary energy demand significantly (International Energy Agency, 2022). The United States' Inflation Reduction Act of 2022 provides tax credits and rebates for homeowners undertaking energy-efficient upgrades, including a 30% tax credit for renewable energy systems (U.S. Environmental Protection Agency, 2022). In the United Kingdom, the Great British Insulation Scheme allocates £1 billion to assist households in improving home insulation, thereby enhancing energy efficiency (Ofgem, 2023). Complementing these governmental efforts, the rise of green finance instruments such as sustainability-linked loans and power purchase agreements is unlocking new avenues for private investment, aligning environmental performance with economic opportunity.

Such mechanisms not only support innovation and diffusion of green infrastructure but also democratize access to sustainable building practices across diverse socioeconomic groups.

4.6 Sustainability through circular building materials

The selection of materials used in constructing energy-driven circular buildings is crucial in achieving sustainability and energy efficiency. Bio-based materials such as bamboo and hempcrete not only offer superior thermal and acoustic insulation but also store carbon, reducing the overall carbon footprint of the building (Chenari et al., 2021; Sun et al., 2021; Cirella et al., 2021). Bamboo, for example, is a rapidly renewable resource with high strength-to-weight properties, making it an excellent alternative to traditional building materials. Similarly, hempcrete, a composite material made from hemp fibers and lime, provides excellent insulation while being lightweight and highly durable (Brás et al., 2019; Kharbouch et al., 2017). In addition to its structural benefits, hempcrete also regulates indoor humidity levels by absorbing and releasing moisture, further improving the comfort and energy efficiency of a building. Another bio-based material gaining popularity is mycelium, a fungal-based material that can be grown into various shapes and used for insulation and lightweight structural components (Mnasri et al., 2017; Le et al., 2023). Mycelium-based products are not only biodegradable but also have fire-resistant and sound-absorbing properties, making them highly advantageous in sustainable construction.

The use of recycled materials, such as reclaimed steel and concrete, further supports circular building practices by minimizing the demand for virgin resources and decreasing the environmental impact associated with material extraction and processing (Huang and Xu, 2009; Cirella et al., 2021; Doczy and AbdelRazig, 2017). Innovations in material recycling such as self-healing concrete and 3D-printed construction components are advancing sustainable building practices by reducing material waste and extending structural lifespans. For example, self-healing concrete has been piloted in infrastructure projects like the Delft University parking garage in the Netherlands and the A14 highway in the UK, reducing maintenance costs and extending service life by up to 30% (Wiktor and Jonkers, 2011; Sangadji et al., 2017). Similarly, 3D-printed concrete has been applied in housing projects in Eindhoven and Dubai, cutting construction waste by up to 60% and reducing material use by 30% through additive precision (Hager et al., 2016; Abedi et al., 2025). These technologies not only minimize environmental footprints but also open new pathways for circularity in structural materials.

Additionally, phase-change materials (PCMs) are being embedded into building elements such as gypsum boards, floor screeds, and roofing panels to enhance thermal regulation and reduce energy demands. Studies show that PCMs can reduce heating and cooling energy consumption by 15–30% in temperate climates (Jaradat et al., 2023; Lamrani et al., 2021), contributing to carbon footprint reductions of up to 20 kg CO_2 per square meter annually (Tonellato et al., 2025). Practical applications include residential pilot buildings in Zaragoza, Spain, and office retrofits in Tokyo, where PCMs were integrated into wall systems and significantly flattened indoor temperature fluctuations (Shree et al., 2025; Abedi et al., 2025). These technologies thus support both energy efficiency and thermal comfort in a wide range of building types and climatic zones.

The widespread adoption of sustainable building materials is being supported by policy interventions and business innovations. Regulatory frameworks now encourage the use of environmentally friendly construction materials, while certification programs such as LEED (Leadership in Energy and Environmental Design) provide incentives for developers to incorporate sustainable materials into their projects (Blomsma and Brennan, 2017; Lieder and Rashid, 2016). For example, in the United States, cities such as Washington, D.C., and Boston mandate that all new public buildings meet at least LEED Silver certification, with incentives provided for private developers to exceed these benchmarks (Blomsma and Brennan, 2017). Similarly, San Francisco's Green Building Code requires all new commercial buildings over 25,000 square feet to achieve LEED Gold or higher. These mandates are reinforced by financial incentives, such as tax abatements, expedited permitting, and grants for renewable energy and sustainable material integration (Lieder and Rashid, 2016). Internationally, Singapore's Green Mark Scheme, which parallels LEED, has successfully pushed for large-scale adoption of sustainable practices in both private and public sectors, supported by regulatory requirements and state-backed subsidies. Thus, governments and organizations are implementing building codes that prioritize the use of recycled and low-carbon materials, promoting greater sustainability in the built environment. Furthermore, businesses are investing in research and development to expand the range of available sustainable materials, making them more cost-effective and accessible for large-scale construction projects.

Material passports, a concept gaining traction in circular construction, involve digitally documenting the composition, origin, and recyclability of building materials. This enables future reuse and recycling, ensuring that materials retain their value and do not become waste at the end of a building's life cycle (Mao and Cao, 2025; Çetin et al., 2023; Markou et al., 2025). However, through adopting material passports and lifecycle assessments, architects and engineers can make informed decisions that maximize the sustainability and efficiency of construction projects (Markou et al., 2025; Çetin et al., 2023).

Scalability remains a central concern in deploying these innovations across rapidly urbanizing regions. While modular design offers an efficient, low-waste construction method with reduced labor needs and faster assembly times, scaling it requires robust logistics networks, regulatory alignment, and investment in prefabrication facilities (Kibert and Fard, 2012; Hobson et al., 2020). Similarly, integrating renewable energy systems like photovoltaic facades or solar-integrated windows at scale involves addressing challenges related to grid capacity, maintenance expertise, and high initial costs (Ahmadi et al., 2020; Adams, 2016). However, opportunities abound governments can leverage public-private partnerships, green financing mechanisms, and urban master planning to mainstream circular material adoption in large-scale housing and infrastructure developments. Emerging economies, especially, can benefit from leapfrogging outdated practices by embedding energy-driven circular strategies directly into their development frameworks.

Overall, the shift toward circular building materials is reshaping the construction industry, leading to reduced environmental impact, improved energy efficiency, and increased resilience in the built environment. As technological advancements continue to drive material innovation, the adoption of circular materials will play a critical role in achieving net-zero carbon goals and fostering long-term sustainability in construction (see Figure 4).

However, the benefits of adopting energy-driven circular architecture are manifold. Focusing on energy efficiency and the circular use of resources, buildings can drastically reduce their environmental impact, leading to lower carbon emissions, waste reduction, and more sustainable energy consumption patterns (Cirella et al., 2021; Olatunde et al., 2024; Liu and Wu, 2022). In addition, the circular approach can enhance the economic viability of buildings by lowering long-term operational costs and providing opportunities for innovation in design and material use. Buildings that are designed for flexibility and adaptability are better equipped to meet changing user needs and market conditions, thereby improving their longevity and reducing the need for demolition or extensive renovation (Kotsopoulos, 2022; Hensen and Lamberts, 2011; Kibert and Fard, 2012).

Conversely, there are several challenges associated with implementing these strategies on a large scale. One of the primary obstacles is the high initial cost of incorporating circular design principles and energy-efficient technologies. While these strategies may result in long-term savings, the upfront investment can be a barrier for developers and builders (Hobson et al., 2020; Williams et al., 2023; Ahmadi et al., 2020; Abanda et al., 2021; Adams, 2016). Additionally,

FIGURE 4
Outlines a systemic approach to energy-driven circular architecture, combining modular design, recyclable materials, and energy-efficient systems with green infrastructure to create adaptable, regenerative, and sustainable built environments. Source: Developed by the Authors.

the availability and cost of circular materials, as well as the need for skilled labor and expertise in modular construction, can limit the widespread adoption of circular architecture (Jones et al., 2019; Chenari et al., 2021; Cristino et al., 2021). Regulatory frameworks and building codes often lag behind the innovations in sustainable construction, creating uncertainty for architects and developers looking to implement energy-driven circular strategies (Lieder and Rashid, 2016).

Energy-driven circular architecture represents a transformative approach to sustainable building design. Thus, combining modular construction, energy-efficient systems, renewable energy sources, and circular materials, buildings can significantly reduce their environmental impact while providing long-term benefits for society. However, continued research and innovation, along with the development of supportive policies, will be essential to realizing the full potential of this paradigm in the coming years.

5 Technological innovations in energy-driven circular design

The growing emphasis on energy-driven circular design has catalyzed a wave of technological innovations that improve building energy efficiency and sustainability. Key advancements in smart building technologies and renewable energy integration are pivotal in shaping the future of sustainable architecture, focusing on optimizing energy usage, reducing waste, and contributing to a more resilient and environmentally conscious built environment.

At the core of energy-driven circular design, smart building technologies play a transformative role in managing energy consumption, optimizing resource use, and minimizing operational costs (Sachs, 2015; Chenari et al., 2021; Cristino et al., 2021). These technologies, which include sensors, automation systems, and data analytics, facilitate the real-time adjustment of lighting, heating, ventilation, and air conditioning (HVAC) systems based on environmental conditions and occupancy patterns (Cirella et al., 2021; Bell et al., 2022; Azar and Menassa, 2014; Frosch and Gallopoulos, 1989). Through tailoring energy use to actual demand, smart systems not only improve building efficiency but also reduce energy waste, aligning with the principles of circularity.

The integration of digital technologies such as Building Information Modeling (BIM), the Internet of Things (IoT), and Artificial Intelligence (AI) further enhances the management of energy systems throughout a building's lifecycle (Jones et al., 2019; Horne, 2017; Parker et al., 2021). BIM allows for advanced modeling of building systems, facilitating the optimization of energy efficiency from the design phase (Abanda et al., 2021; Ntasiou and Andreou, 2017; Rios et al., 2022; Rajput and Singh, 2019). IoT devices enable seamless communication between building components, allowing for real-time monitoring and automated control to ensure energy-efficient operations (Farzaneh et al., 2021; Rios et al., 2022; Wang et al., 2017). AI-driven algorithms enhance predictive capabilities, enabling systems to anticipate and respond to changes in building use, weather conditions, and energy demand, thereby increasing operational efficiency and supporting a low-carbon, sustainable living environment (Farzaneh et al., 2021; Wang et al., 2017; Sun et al., 2021).

Moreover, the data generated by these technologies provides valuable insights that can inform continuous improvements in energy use and system performance, ensuring buildings remain optimized for sustainability and circularity over time (Cristino et al., 2021; Sun et al., 2021; Ürge-Vorsatz et al., 2020). Furthermore, as buildings evolve, these technologies allow for adaptive modifications that overlaps with changing energy requirements and environmental conditions, making smart building systems an essential tool for achieving long-term sustainability goals.

Renewable energy integration is another critical aspect of energy-driven circular design, with technologies such as solar, wind, and geothermal systems playing an essential role in reducing dependence on fossil fuels and lowering the carbon footprint of the built environment (Sachs, 2015; Yu et al., 2024). The integration of these technologies within buildings not only provides clean energy but also supports the shift towards a circular economy by reducing the need for non-renewable resources and encouraging self-sufficiency in energy production (Wags and Ifeanyi, 2024; Wang et al., 2017; Williams et al., 2023; Yu et al., 2024).

Solar panels, for instance, offer a scalable solution for harnessing renewable energy on-site, directly powering buildings while mitigating reliance on external energy sources. The deployment of wind and geothermal energy technologies further diversifies energy production options, enhancing the resilience of buildings to energy supply disruptions (Sebestyén, 2021; Wang et al., 2017; Zaniboni and Albatici, 2022; Lu et al., 2020). Therefore, integrating such renewable energy systems into buildings, the design becomes more flexible and capable of adapting to fluctuating energy demands and available resources.

One of the challenges in renewable energy integration, particularly in buildings, is dealing with intermittent energy supply. Energy storage systems, such as batteries and thermal storage, are essential for mitigating this issue. These technologies store surplus energy generated during peak production periods and release it during times of low energy generation, thus ensuring continuous and reliable energy supply (Sathaye et al., 2011; Lu et al., 2020; Jones et al., 2019; Parker et al., 2021). The coupling of renewable energy sources with energy storage solutions contributes significantly to the efficiency and resilience of buildings, while supporting the broader goal of transitioning to low-carbon and sustainable urban environments (Kibert and Fard, 2012; Zaniboni and Albatici, 2022; Sathaye et al., 2011).

In addition to on-site renewable energy generation, the application of renewable energy technologies at the district or urban scale further enhances the potential for circular economies. Thus, creating energy-sharing networks among buildings and communities, the integration of distributed renewable energy systems can lead to more efficient use of resources and reduce the overall demand for centralized energy infrastructure (Rios et al., 2022; Sathaye et al., 2011; Sun et al., 2021; Ruparathna et al., 2016). These systems facilitate the exchange of energy between buildings, making the energy supply more resilient, flexible, and sustainable.

The integration of smart building technologies and renewable energy systems within energy-driven circular design frameworks is an embodiment of circular economy principles. Circularity in the built environment extends beyond resource recovery and recycling to encompass the continuous optimization of energy, materials, and processes throughout the building's lifecycle (Blomsma and Brennan, 2017; Geissdoerfer et al., 2017). Moreso, by leveraging technologies such as BIM, IoT, AI, and renewable energy systems, the circular economy in buildings ensures that resources are used efficiently and waste is minimized at every stage from design and construction to operation and deconstruction (Wang et al., 2017; Olatunde et al., 2024; Wags and Ifeanyi, 2024).

As part of this broader circular approach, innovations such as the use of reclaimed materials, energy-efficient building designs, and the modularization of building components further contribute to the sustainability and resilience of the built environment (Bocken et al., 2016; Adams, 2016). The application of these principles, combined with cutting-edge technologies, promotes the reduction of energy and material consumption, facilitating a closed-loop system where resources are reused, remanufactured, and recycled at the end of their useful life (Lieder and Rashid, 2016; Sathaye et al., 2011; Kumar and Cao, 2021).

The shift towards circularity in the built environment also emphasizes the importance of adaptability. Smart systems and renewable energy technologies enable buildings to respond dynamically to changes in environmental conditions, occupancy, and energy demand. This adaptability is crucial in addressing the challenges posed by climate change, where the building sector must account for increasingly extreme weather conditions and evolving energy needs (Bell et al., 2022; Hensen and Lamberts, 2011; Lin and Chen, 2022). However, enabling buildings to function more efficiently, reduce their environmental impact, and contribute to a circular economy, these technological innovations foster the creation of resilient, sustainable urban spaces that can thrive in the face of global environmental challenges (see Figure 5).

6 Transforming urban futures: integrating the UN SDGs into energy-driven circular design for sustainable cities

The integration of the United Nations Sustainable Development Goals (SDGs) into energy-driven circular design presents a powerful framework for rethinking architecture and urban infrastructure. As urbanization accelerates and environmental challenges intensify, it is critical to consider how circular design principles can support sustainable, resilient, and equitable urban development. These

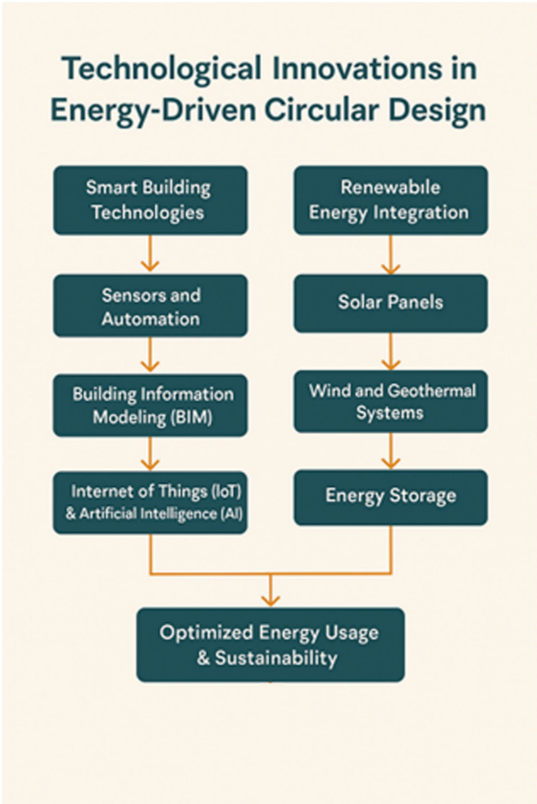

FIGURE 5
Highlights espouses how smart building technologies and renewable energy integration drive energy-driven circular design toward optimized energy usage and sustainability by dynamically managing energy consumption, reducing waste, and ensuring adaptability in the built environment through automation, AI-driven analytics, IoT, and BIM, which enable real-time adjustments in HVAC, lighting, and resource allocation while integrating solar, wind, and geothermal systems to enhance self-sufficiency and resilience by coupling them with energy storage solutions that mitigate intermittent power supply challenges, ultimately fostering a closed-loop system aligned with circular economy principles that minimize waste and ensure buildings remain adaptive to climate uncertainties and evolving energy demands, thereby emphasizing the critical need for policy-driven urban sustainability models that support long-term resilience, efficiency, and environmental responsibility. Source: Developed by the Authors.

principles focus on optimizing resource use, reducing waste, and fostering long-term sustainability in the built environment, all of which directly contribute to the achievement of the SDGs. This section explores the interconnection between key SDGs and energy-driven circular design, demonstrating how these approaches offer innovative solutions to contemporary urban sustainability challenges.

The intersection of SDG 7 and energy-driven circular design is fundamental for reducing energy consumption in the built environment. The promotion of energy-efficient buildings and renewable energy integration is central to achieving this goal. Circular design principles prioritize energy optimization through passive design strategies, efficient building systems, and the use of renewable energy sources such as solar, wind, and geothermal (Abanda et al., 2021; Wang et al., 2017; Olatunde et al., 2024). Additionally, incorporating energy-efficient materials and advanced technologies such as phase change materials and 3D-printed building components facilitates energy savings while reducing dependency on fossil fuels (Bayat and Kashani, 2025; Sachs, 2015; Mushtaha et al., 2021). By reducing energy demand and enhancing energy efficiency, energy-driven circular design plays a pivotal role in making energy more accessible, sustainable, and resilient, thereby contributing to SDG 7.

However, SDG 11 advocates for inclusive, safe, resilient, and sustainable cities, and circular economy principles offer a direct path toward meeting this goal. Circular design strategies in urban planning such as the reuse, recycling, and repurposing of materials help mitigate waste and lower environmental footprints (Mnasri et al., 2017; Lu et al., 2020). The adoption of bio-based materials and reclaimed resources is one such example, showcasing how sustainable construction practices contribute to long-term resilience against climate change impacts (Blomsma and Brennan, 2017; Brás et al., 2019; Lee et al., 2022). Moreover, energy-efficient infrastructure not only reduces energy consumption but also enhances the durability of urban structures, ensuring that cities can withstand evolving environmental challenges. As urban areas continue to expand, integrating circular principles into the built environment can create sustainable cities that meet both ecological and social sustainability targets, supporting SDG 11.

Moreover, achieving SDG 12 requires a significant shift toward sustainable consumption and production patterns. In the built environment, this can be achieved through circular construction techniques, which prioritize resource efficiency, waste reduction, and material longevity. Circular economy strategies such as material passports, eco-design, and adaptive reuse allow for buildings to be disassembled and repurposed, ensuring that materials remain in productive use throughout their lifecycle (Çetin et al., 2023). As highlighted by Chenari et al. (2021), green infrastructure further enhances energy efficiency by promoting eco-friendly building practices that reduce the environmental impact of construction. By focusing on the sustainable lifecycle of materials and promoting responsible production practices, energy-driven circular design supports SDG 12's objective of reducing waste and fostering more sustainable industrial practices.

Furthermore, SDG 13 calls for urgent action to combat climate change, and the built environment is a key sector in addressing this challenge. Nearly 40% of global energy consumption is attributed to buildings, making it a significant source of carbon emissions (Hager et al., 2016). Energy-driven circular design offers an effective strategy for reducing emissions by promoting energy-efficient buildings and adaptive reuse of materials. Advanced technologies, such as energy simulation tools, can predict future climate impacts on buildings, enabling the design of structures that are both energy-efficient and resilient to climate change (Bell et al., 2022; Invidiata et al., 2018; Horne, 2017). Through incorporating circular principles such as the reuse of materials, design for adaptability, and the integration of renewable energy buildings can not only reduce their carbon footprint but also support the global transition to a low-carbon economy, directly contributing to SDG 13.

Finally, SDG 9 focuses on fostering resilient infrastructure, promoting sustainable industrialization, and driving innovation. The role of technological innovation is crucial in achieving energy-driven circular design. Technologies such as Building Information Modeling (BIM) and 3D printing facilitate precise material usage, reducing waste and optimizing energy efficiency (Himeur et al., 2021; Hager et al., 2016; Hafez et al., 2023). Additionally, the incorporation of smart technologies such as energy management systems and automation into building design further enhances the performance and sustainability of urban infrastructure (Farzaneh et al., 2021; Abedi et al., 2025). These innovations are instrumental in creating resilient, sustainable infrastructure that aligns with SDG 9's goal of transforming industries and infrastructure to be more inclusive, sustainable, and energy efficient (see Figure 6).

7 Challenges and opportunities in energy-driven circular design

The integration of energy-driven circular design in the built environment offers promising potential for reducing resource consumption, minimizing waste, and achieving energy efficiency (Lin and Chen, 2022; Sachs, 2015; Lee et al., 2022). However, several technical and economic barriers must be addressed to fully realize its potential. The technical challenges involve the integration of renewable energy systems into existing infrastructures, the adaptation of buildings to new energy models, and the implementation of advanced materials and technologies (Kumar and Cao, 2021; Kotsopoulos, 2022; Kibert and Fard, 2012). These challenges often require extensive retrofitting and upgrading of current systems to ensure they align with the principles of circular economy and energy efficiency. In particular, the integration of decentralized renewable energy sources, such as solar panels and wind turbines, can be complex, especially when applied to older or less adaptable buildings (Abanda et al., 2021; Blomsma and Brennan, 2017; Mahmood et al., 2022).

The high upfront costs associated with the adoption of energy-efficient building technologies are a significant deterrent to the widespread application of circular design principles (Wang et al., 2017; Olatunde et al., 2024; Nisar et al., 2024). Sustainable building materials, energy-efficient appliances, and renewable energy systems, while beneficial in the long run, often come with significant initial costs that can deter both developers and property owners from investing in these technologies (Parker et al., 2021; Sathaye et al., 2011; Sun et al., 2021). This is particularly true in markets where financial resources are constrained, and where the return on investment (ROI) for sustainable design solutions may take several years to materialize. Furthermore, the lack of standardized methods for evaluating the long-term economic benefits of circular design further complicates decision-making processes for stakeholders in the construction and

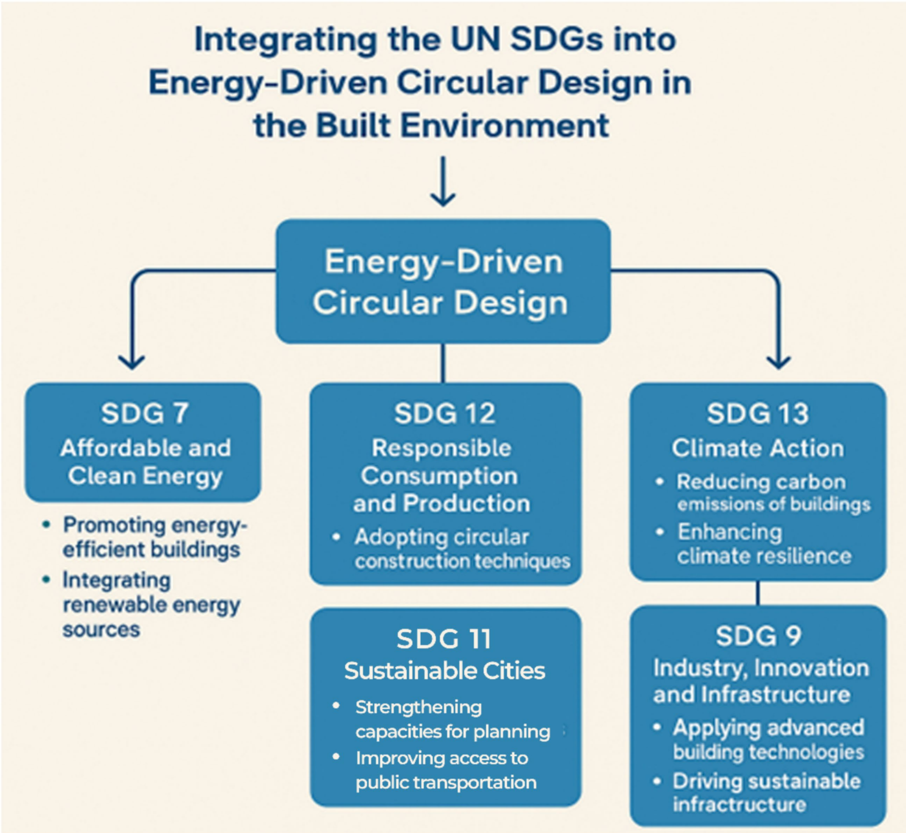

FIGURE 6
Conceptualizes specific UN SDGs in relation to circular design in the built environment. Source: Developed by the Authors.

real estate sectors (Bocken et al., 2016; Chenari et al., 2021; Ruparathna et al., 2016).

From an economic perspective, the transition to energy-driven circular design requires a shift in both thinking and practices. The adoption of circular economy principles often demands substantial upfront capital investment in technologies such as energy-efficient systems, renewable energy installations, and environmentally sustainable materials (Jones et al., 2019; Vink and Vinke-de Kruijf, 2024; Sebestyén, 2021). The long-term economic viability of these solutions, however, lies in their ability to generate operational savings, increase property value, and future-proof buildings against energy price fluctuations and environmental regulation changes (Azar and Menassa, 2014; Van Ewijk et al., 2023; Lee et al., 2022). The energy savings accrued from such investments, alongside the decreasing operational costs associated with renewable energy systems, can offset the initial high costs, making energy-driven circular design an economically viable option in the long term (Kotsopoulos, 2022; Ruparathna et al., 2016; Kibert and Fard, 2012).

One of the significant challenges within this economic landscape is the uncertainty of financial incentives. While there is growing awareness of the long-term benefits of energy-efficient designs, developers and investors may remain hesitant to commit to costly circular economy solutions without clear economic incentives or guarantees. This is particularly true in regions with limited government support, where regulatory frameworks may not yet fully encourage energy-driven circular practices. However, this presents an opportunity for innovation in financial models and investment strategies that emphasize lifecycle cost savings, energy performance metrics, and the resilience of green buildings to market fluctuations (Geissdoerfer et al., 2017; Horne, 2017; Lin and Chen, 2022).

Governmental support plays a pivotal role in driving the transition to energy-driven circular design, particularly through the establishment of effective policy and regulatory frameworks (Hensen and Lamberts, 2011; Gillott et al., 2023; Hauge et al., 2011; Cirella et al., 2021). Policy incentives, such as tax incentives, grants, and subsidies for energy-efficient technologies, can significantly lower the financial barrier for adoption. Moreover, the implementation of regulations that mandate energy-efficient building codes and environmentally sustainable construction practices can push the construction sector toward adopting circular economy models (Cirella et al., 2021; Elshafei et al., 2022; Doczy and AbdelRazig, 2017). Policies that encourage the use of renewable energy sources, such as solar, wind, and geothermal systems, can ensure that the energy needs of buildings are met through sustainable means, reducing dependency on non-renewable energy sources and contributing to a greener built environment (De Jesus and Mendonça, 2018; Ruparathna et al., 2016; Farzaneh et al., 2021).

At the national and international levels, the promotion of circular economy policies and frameworks that support energy-driven design has the potential to create a more conducive environment for the development of sustainable building practices. Countries like Denmark, the Netherlands, and Sweden have pioneered circular economy models in their building sectors, integrating energy efficiency and sustainability into their national policy agendas. These policies create a favorable environment for architects, developers, and construction companies to invest in circular design principles without the fear of market instability or policy reversals (Sachs, 2015; Zaniboni and Albatici, 2022; Wang et al., 2017).

However, for these policies to be effective, there needs to be a collaborative effort among all stakeholders involved in the design, construction, and management of buildings. Governments must engage with private sector actors, non-governmental organizations, and academic institutions to develop and implement policies that not only incentivize the adoption of circular design but also promote education and capacity-building in sustainable construction practices (Williams et al., 2023; Sebestyén, 2021; Sathaye et al., 2011). This would involve providing resources for knowledge-sharing and capacity-building initiatives aimed at both industry professionals and the public, fostering widespread awareness of the benefits of energy-driven circular design (Blomsma and Brennan, 2017; Cirella et al., 2021; Jones et al., 2019).

On a global scale, international agreements and frameworks can provide the necessary regulatory support to accelerate the shift toward energy-driven circular design in the built environment. The United Nations' Sustainable Development Goals (SDGs) and the Paris Agreement on climate change, for example, have created a global framework that encourages countries to integrate sustainability into their development agendas. This global push can drive the adoption of sustainable building practices and energy-driven circular design, creating an interconnected and collaborative global effort to address climate change and resource scarcity (Sathaye et al., 2011; Van Ewijk et al., 2023; Olatunde et al., 2024; Hobson et al., 2020).

Despite the progress made in policy support, challenges remain in terms of the implementation and enforcement of these policies. In many regions, local governments may lack the financial resources or technical expertise to enforce energy efficiency standards and ensure compliance with sustainable building codes (Himeur et al., 2021; Farzaneh et al., 2021; Elshafei et al., 2022). A persistent challenge in implementing energy-driven circular design is the disconnect between national policy ambitions and local-level execution. For instance, while the EU's Circular Economy Action Plan promotes uniform sustainability targets, cities like Naples (Italy) and Bucharest (Romania) have struggled with enforcement due to weak municipal capacity and fragmented governance (Blomsma and Brennan, 2017; Himeur et al., 2020). Conversely, Amsterdam's Circular Strategy 2020–2025 demonstrates how adaptive, inclusive policy developed through public-private partnerships and community co-design can localize national goals effectively (Gillott et al., 2023; Horne, 2017). These examples underline the need for flexible, place-based governance models that empower local actors as key drivers of circular and energy-resilient transformations.

Consequently, while challenges remain, there are numerous opportunities within the energy-driven circular design landscape that can accelerate the adoption of sustainable building practices (Bell et al., 2022; Hauge et al., 2011; Habibi and Kahe, 2024). Thus, technological advancements continue to evolve, innovations in energy-efficient systems, smart technologies, and sustainable materials are driving the shift toward circularity (Jones et al., 2019; Himeur et al., 2021). For example, the development of energy storage technologies, such as advanced batteries and thermal storage systems, has the potential to increase the efficiency of renewable energy systems in buildings, ensuring a reliable and sustainable energy supply (Bell et al., 2022; Frosch and Gallopoulos, 1989; Williams et al., 2023).

In addition, the growing emphasis on circular economy principles has opened up new avenues for business models within the construction sector. Companies are increasingly exploring opportunities to implement closed-loop systems that reduce waste and maximize resource recovery (Huang et al., 2022; Lin and Chen, 2022). This has led to the creation of innovative building materials, such as those made from recycled materials or biodegradable substances, which offer both environmental and economic advantages (Lee et al., 2022; Horne, 2017; Hobson et al., 2020). Therefore, focusing on reducing the need for virgin materials and enabling the reuse and recycling of materials at the end of their lifecycle, the construction industry can significantly reduce its environmental footprint while promoting resource efficiency (Bocken et al., 2016; Geissdoerfer et al., 2017; Nisar et al., 2024).

Furthermore, circular economy principles are increasingly being integrated into building design using smart technologies that optimize energy performance. For instance, advanced building management systems (BMS), which incorporate sensors, artificial intelligence, and data analytics, can continuously monitor and adjust energy consumption in real-time (Himeur et al., 2020; Parker et al., 2021; Sebestyén, 2021; Wags and Ifeanyi, 2024). These systems enable buildings to become more adaptive to their occupants' needs while reducing overall energy use and improving comfort levels (Farzaneh et al., 2021; Himeur et al., 2020; Ürge-Vorsatz et al., 2020).

Therefore, leveraging the potential of these technologies and policy frameworks, energy-driven circular design can transform the built environment into a more sustainable, resilient, and resource-efficient system. No doubt as the challenges of integrating circular principles are addressed, the opportunities to innovate, create value, and promote sustainability become increasingly clear (Vink and Vinke-de Kruijf, 2024; Sun et al., 2021; Zaniboni and Albatici, 2022). While there are significant barriers to the widespread adoption of energy-driven circular design in the built environment, the potential benefits far outweigh the challenges. Through the continued development of technological innovations, supportive policy frameworks, and a collective commitment to sustainability, the built environment can transition toward a more circular, energy-efficient future.

7.1 Recommendations for advancing energy-driven circular design in the built environment

7.1.1 Enhanced technological innovation and research

To fully realize the potential of energy-driven circular design, continuous investment in the development and refinement of energy-efficient technologies and renewable energy systems is essential. Research should focus on improving the scalability and cost-effectiveness of smart building systems, energy storage solutions, and circular construction materials. Encouraging the adoption of energy-positive buildings and integrating next-generation technologies such as Artificial Intelligence (AI) and the Internet of Things (IoT) will optimize energy consumption and resource management across the building lifecycle. However, technological innovation in energy-driven circular design faces several challenges, especially in regions with limited resources or technical expertise.

The immaturity of many energy-efficient technologies and renewable energy systems can hinder their scalability and widespread adoption. While solutions like solar panels, energy storage, and AI-powered energy management systems are promising, they often remain expensive and require highly specialized knowledge for implementation. Additionally, in developing countries, the lack of technical expertise and infrastructure to support such advanced technologies can create a significant barrier. This is particularly true for industries that are not yet accustomed to sustainable building practices or energy-efficient technologies.

Thus, one approach to overcoming technological barriers is to foster international collaboration and knowledge sharing, enabling the exchange of research findings, best practices, and technologies between developed and developing regions. Governments and international organizations can play a pivotal role by facilitating technology transfer programs that offer training and technical assistance to local professionals. Furthermore, the establishment of low-cost pilot projects and demonstration buildings, particularly in resource-constrained settings, can help prove the viability and benefits of energy-driven circular design technologies. Incentivizing public-private partnerships can also alleviate financial burdens and accelerate the commercialization of new technologies. Finally, developing adaptable, region-specific solutions that take into account local environmental conditions and material availability can enhance the feasibility of these innovations in diverse contexts.

7.1.2 Policy and regulatory frameworks

Governments must create and implement comprehensive policy frameworks that incentivize the adoption of circular design practices. Regulations should support energy efficiency, waste reduction, and the use of sustainable building materials. Establishing tax incentives, subsidies, and financial support for companies that prioritize sustainable construction and energy-efficient technologies will accelerate the shift towards circularity. Additionally, introducing stricter regulations on waste management and recycling in the construction industry can enhance the viability of circular materials and systems.

One of the key challenges in implementing effective policy frameworks for energy-driven circular design is the lack of robust regulatory infrastructure in regions with limited governance capacity. In many low- and middle-income countries, local governments may lack the technical expertise, institutional capacity, or political will to create and enforce effective policies. Even in wealthier regions, there may be resistance from powerful construction industry stakeholders who prioritize short-term profits over long-term sustainability goals. Furthermore, in areas with limited financial resources, the upfront cost of implementing energy-efficient systems and circular construction methods can be seen as prohibitive, even when long-term savings are apparent.

To overcome these regulatory and enforcement barriers, it is crucial to adopt adaptive governance models. These models are flexible, allowing policies to evolve in response to changing technological, economic, and social contexts. Governments can develop localized policy frameworks that align with the specific needs, capacities, and cultural contexts of different regions, instead of relying on one-size-fits-all regulations. Localized frameworks can consider the availability of materials, technological capabilities, and economic conditions.

Moreover, the involvement of multiple stakeholders including private sector actors, civil society, and local communities can help ensure that regulations are both feasible and well-supported. In regions where enforcement is weak, governments can establish mechanisms that rely on voluntary compliance, initially offering financial incentives and support to companies adopting energy-efficient and circular design practices. Over time, these voluntary programs can evolve into mandatory regulations as local capacity for enforcement increases. Additionally, international aid and development organizations can offer technical support and financial resources to help local governments build the necessary infrastructure for enforcing sustainability policies.

7.1.3 Collaboration across stakeholders

Effective collaboration between architects, urban planners, engineers, developers, and policymakers is crucial for overcoming barriers to circular design adoption. Interdisciplinary cooperation will facilitate the integration of circular design principles into every stage of building design, construction, and operation. It is essential to foster dialogue between the private and public sectors to develop sustainable solutions that balance economic growth with long-term environmental sustainability.

One of the primary challenges to collaboration is the fragmentation of expertise and interests within the construction industry. Architects, engineers, urban planners, and developers may have different priorities, leading to conflicts or misunderstandings about the feasibility of energy-driven circular design strategies. Additionally, the highly competitive nature of the construction industry may discourage collaboration, as companies prioritize proprietary technologies and cost-saving measures over collective efforts to advance sustainability goals. In some regions, cultural and political barriers may further complicate cooperation, particularly if there is a lack of trust between the public and private sectors.

To overcome these barriers, it is essential to establish cross-disciplinary platforms that bring together diverse stakeholders and foster collaboration from the outset of building projects. These platforms could take the form of workshops, collaborative planning sessions, or joint research initiatives that allow stakeholders to share their knowledge, identify common goals, and align their interests. Creating a shared vision for sustainability, along with clear guidelines and standards, can help bridge gaps between different disciplines. Furthermore, governments can incentivize collaboration by offering financial or regulatory benefits to projects that demonstrate integrated, cross-sectoral cooperation. Finally, fostering a culture of sustainability within the construction industry through industry-wide initiatives can help overcome resistance to collaboration and encourage stakeholders to work together toward common sustainability objectives.

7.1.4 Education and training

To ensure the widespread implementation of energy-driven circular design, education and training programs should be developed for professionals in the construction and architecture sectors. Providing the necessary tools, knowledge, and skill sets will empower individuals to incorporate sustainable practices into their work, driving innovation and fostering a culture of sustainability within the industry.

In many regions, especially those with limited resources, there may be a skills gap in the construction and architecture sectors. This gap arises from both a lack of formal education in sustainable design practices and insufficient on-the-job training opportunities. The adoption of cutting-edge technologies such as AI, IoT, and advanced energy storage systems requires professionals to possess a high degree of technical knowledge. Furthermore, there may be cultural resistance to adopting new practices, particularly in regions where traditional construction methods have long been the norm.

To address these challenges, governments, universities, and professional organizations can collaborate to develop specialized training programs in energy-driven circular design, focusing on both technical and managerial skills. These programs can be delivered through online platforms, mobile applications, or short courses, making them accessible to professionals in diverse regions. Furthermore, incentive-based models can be implemented, where professionals who complete accredited training programs are eligible for certification or financial rewards. Public-private partnerships can help fund these training initiatives, reducing the financial burden on individuals and organizations. Additionally, promoting local champions individuals or companies that have successfully implemented energy-driven circular design practices can inspire others to follow suit and reduce resistance to change.

7.1.5 Public awareness and engagement

Increasing public awareness of the benefits of energy-driven circular design is vital for gaining widespread support and demand. Educating consumers on the long-term environmental and economic advantages of energy-efficient, circular buildings can encourage the adoption of sustainable living practices and promote greater community involvement in sustainable urban development initiatives.

One of the key challenges to public engagement is the lack of awareness about the potential benefits of energy-driven circular design. In many regions, particularly in developing countries, there may be limited understanding of how these building practices can lead to long-term cost savings and environmental benefits. Furthermore, some communities may be culturally resistant to adopting new building practices, especially if they are unfamiliar or seen as too expensive. Misconceptions about the affordability and feasibility of sustainable building practices can also deter people from embracing circular design principles.

To address these challenges, governments and NGOs can launch awareness campaigns that highlight the tangible benefits of energy-driven circular design, such as lower energy bills, improved indoor air quality, and reduced environmental impact. These campaigns should focus on real-world examples, showcasing successful projects in both developed and developing regions. Additionally, integrating community-based participatory approaches into urban planning can help build trust and support for sustainable design practices, particularly in culturally diverse communities. By involving communities in the planning process and addressing their specific concerns, governments can foster greater acceptance and enthusiasm for energy-efficient, circular buildings.

In essence, while energy-driven circular design offers significant potential to revolutionize the built environment, its widespread implementation is fraught with challenges. Technological immaturity, regulatory gaps, and a lack of public awareness are just a few of the barriers that need to be addressed. However, by adopting adaptive governance models, fostering interdisciplinary collaboration, investing in education and training, and engaging the public, these challenges can be overcome. Through careful, context-specific strategies, the transition toward energy-driven circular design can be accelerated, leading to more sustainable, energy-efficient, and resilient built environments for the future.

8 Conclusion and future outlook

The concept of energy-driven circular design in the built environment is not merely a trend but a crucial necessity in our journey towards a sustainable future. Nowadays cities continue to expand and the global demand for energy intensifies, the built environment will inevitably play a pivotal role in shaping climate resilience and energy efficiency. The integration of energy-efficient systems with circular design principles where resources are reused, recycled, and reduced offers transformative potential to mitigate climate change, conserve natural resources, and reduce environmental degradation. This convergence of energy efficiency and circularity holds promise in creating sustainable, low-carbon cities and buildings that are resilient to future challenges.

At its core, energy-driven circular design is a multifaceted approach that emphasizes the optimization of energy use while ensuring that materials and resources within buildings and cities are cycled back into productive use. This contrasts with the traditional linear models of production and consumption, which have historically led to excessive waste and depletion of finite resources. Circular design offers an alternative, one that aligns with the values of sustainability, resilience, and regeneration. As such, this approach will be indispensable in addressing the formidable challenges posed by climate change and urbanization.

Technological innovation remains one of the primary drivers of this transformation. Advancements in smart building technologies, renewable energy integration, and energy storage solutions have the potential to unlock new levels of efficiency and circularity in the built environment. For instance, buildings that incorporate advanced insulation materials, energy-efficient HVAC systems, and renewable energy sources such as solar panels and wind turbines can dramatically reduce their carbon footprints while ensuring a steady supply of clean energy. Moreover, the use of circular design in construction materials through the reclamation and reuse of materials can minimize the waste generated by demolition and construction activities.

However, despite the immense potential of energy-driven circular design, several barriers must be addressed to unlock its full impact. Technologically, many energy-efficient systems and circular solutions are still in their nascent stages. While innovations such as energy-positive buildings and smart grids show promise, scalability remains a concern. The technologies that underpin these systems must be refined, standardized, and made cost-effective for widespread adoption. Moreover, while circular design offers clear benefits in terms of resource conservation, the adoption of these strategies at scale in the built environment faces challenges in terms of supply chain logistics, cost constraints, and the availability of recyclable materials.

Economic and policy challenges also play a significant role in shaping the trajectory of energy-driven circular design. The economic model that governs construction and urban development often rewards short-term gains over long-term sustainability. Circular design, by its nature, requires upfront investment in research, technology, and systems that may not yield immediate financial returns. This can deter stakeholders from adopting such strategies, especially in regions where immediate economic growth is prioritized over long-term environmental goals. Similarly, regulatory frameworks are often ill-suited to support circular practices. There is a clear need for policies that incentivize circular construction practices, support innovation, and encourage investments in green technologies.

On the policy front, governments have an essential role to play in creating an enabling environment for energy-driven circular design. Policy frameworks should be aligned with broader sustainability goals, such as net-zero emissions and the transition to a circular economy. This can be achieved by enacting regulations that encourage energy efficiency, waste reduction, and the use of renewable resources in building construction. Incentives, such as tax breaks or subsidies, can be provided to businesses that adopt circular practices or invest in energy-efficient technologies. Additionally, policy interventions should address the challenges of circularity in the construction industry, including promoting the recycling of materials, standardizing recycling protocols, and creating markets for second-hand building materials.

Collaboration among various stakeholders ranging from architects, engineers, and urban planners to policymakers, developers, and industry leaders is crucial for achieving the vision of energy-driven circular design. The transition to a sustainable built environment will require collective action and shared knowledge across disciplines. Architects and engineers will need to work closely with policymakers to develop designs that comply with evolving regulations and meet the sustainability criteria set by governments. Developers, in turn, must engage with suppliers of recycled materials and energy-efficient technologies to ensure the practical application of circular principles.

Looking ahead, the potential of energy-driven circular design in the built environment is vast. The future promises a landscape where cities are designed as systems of regeneration rather than consumption, where energy and materials are constantly cycled back into the economy. As building technologies continue to evolve, we are likely to see buildings that are not only energy-efficient but also capable of generating more energy than they consume. Buildings of the future may even serve as hubs of energy production, sharing surplus energy with surrounding communities, thus contributing to the overall energy resilience of urban areas.

Concluding, while the challenges of implementing energy-driven circular design in the built environment are substantial, they are by no means insurmountable. As the world faces the twin crises of climate change and resource depletion, the need for sustainable, resilient, and low-carbon cities and buildings is more pressing than ever. The path forward will require bold thinking, technological innovation, and cooperative efforts across sectors. Therefore, with the right mechanism in place we can create a future where the built environment contributes positively to both the planet and its inhabitants. The potential is enormous, and the time to act is now.

Author contributions

WM: Conceptualization, Investigation, Methodology, Project administration, Supervision, Visualization, Resources, Writing – original draft, Writing – review & editing. GA: Data curation, Visualization, Writing – review & editing.

Funding

The author(s) declare that no financial support was received for the research and/or publication of this article.

Conflict of interest

The authors declare that the research was conducted in the absence of any commercial or financial relationships that could be construed as a potential conflict of interest.

Generative AI statement

The author(s) declare that no Generative AI was used in the creation of this manuscript.

Publisher's note

References

Abanda, F. H., Sibilla, M., Garstecki, P., and Anteneh, B. M. (2021). A literature review on BIM for cities distributed renewable and interactive energy systems. *Int. J. Urban Sustain. Dev.* 13, 214–232. doi: 10.1080/19463138.2020.1865971

Abedi, M., Waris, M. B., Al-Alawi, M. K., Al-Jabri, K. S., and Al-Saidy, A. H. (2025). From local earth to modern structures: A critical review of 3D printed cement composites for sustainable and efficient construction. *J. Build. Eng.* 100:111638. doi: 10.1016/j.jobe.2024.111638

Adams, K. (2016) Important factors to consider for applying circular economy in buildings including a focus on reclamation. #BuildCircular learning hub @ EcoBuild 2016, 8th–10th March 2016, London.

Ahmadi, A. M., Sabori, N. R., and Halim, M. (2020). A typical design for energy-efficient building: a case study of zero energy building. *Repa Proc. Series* 1, 22–31. doi: 10.37357/1068/SODC2019.1.1.03

Azar, E., and Menassa, C. C. (2014). A comprehensive framework to quantify energy savings potential from improved operations of commercial building stocks. *Energy Policy* 67, 459–472. doi: 10.1016/j.enpol.2013.12.031

Aziz, E., and Omar, B. (2020). The impact of building orientation on energy consumption in a domestic house in desert climate.

Bayat, H., and Kashani, A. (2025). Reducing material and energy consumption in single-story buildings through 3D-printed wall designs. *Energ. Buildings* 333:115497. doi: 10.1016/j.enbuild.2025.115497

Bell, N. O., Bilbao, J. I., Kay, M., and Sproul, A. B. (2022). Future climate scenarios and their impact on heating, ventilation and air-conditioning system design and performance for commercial buildings for 2050. *Renew. Sust. Energ. Rev.* 162:112363. doi: 10.1016/j.rser.2022.112363

Blomsma, F., and Brennan, G. (2017). The emergence of circular economy: A new framing around prolonging resource productivity. *J. Ind. Ecol.* 21, 603–614. doi: 10.1111/jiec.12603

Bocken, N. M. P., de Pauw, I., Bakker, C., and van der Grinten, B. (2016). Product design and business model strategies for a circular economy. *Journal of Industrial and Production Engineering* 33, 308–320. doi: 10.1080/21681015.2016.1172124

Brás, A., Antunes, A., Laborel-Préneron, A., Ralegaonkar, R., Shaw, A., Riley, M., et al. (2019). Optimisation of bio-based building materials using image analysis method. *Constr. Build. Mater.* 223, 544–553. doi: 10.1016/j.conbuildmat.2019.06.148

Çetin, S., Raghu, D., Honic, M., Straub, A., and Gruis, V. (2023). Data requirements and availabilities for material passports: A digitally enabled framework for improving the circularity of existing buildings. *Sustainable Prod. Consumption* 40, 422–437. doi: 10.1016/j.spc.2023.07.011

Chatzimentor, A., Apostolopoulou, E., and Mazaris, A. D. (2020). A review of green infrastructure research in Europe: challenges and opportunities. *Landsc. Urban Plan.* 198:103775. doi: 10.1016/j.landurbplan.2020.103775

Chen, X., Liu, Z., Saydaliev, H. B., Abu Hatab, A., and Fang, W. (2021). Measuring energy efficiency performance in China: do technological and environmental concerns matter for energy efficiency? *Front. Energy Res.* 9:779032. doi: 10.3389/fenrg.2021.779032

Chenari, B., Dias Carrilho, J., and Gameiro da Silva, M. (2021). Towards sustainable, energy-efficient and healthy ventilation strategies in buildings: A review. *Renew. Sust. Energ. Rev.* 59, 1426–1447. doi: 10.1016/j.rser.2016.01.074

Cheshmehzangi, A., Butters, C., Xie, L., and Dawodu, A. (2021). Green infrastructures for urban sustainability: issues, implications, and solutions for underdeveloped areas. *Urban For. Urban Green.* 59:127028. doi: 10.1016/j.ufug.2021.127028

Cirella, G. T., Russo, A., Benassi, F., Czermański, E., Goncharuk, A. G., and Oniszczuk-Jastrzabek, A. (2021). Energy re-shift for an urbanizing world. *Energies* 14:5516. doi: 10.3390/en14175516

Cristino, T. M., Lotufo, F. A., Delinchant, B., Wurtz, F., and Faria Neto, A. (2021). A comprehensive review of obstacles and drivers to building energy-saving technologies and their association with research themes, types of buildings, and geographic regions. *Renew. Sustain. Energy Rev.* 135:110191. doi: 10.1016/j.rser.2020.110191

De Jesus, A., and Mendonça, S. (2018). Lost in transition? Drivers and barriers in the eco-innovation road to the circular economy. *Ecol. Econ.* 145, 75–89. doi: 10.1016/j.ecolecon.2017.08.001

Doczy, R., and AbdelRazig, Y. (2017). Green buildings case study analysis using AHP and MAUT in sustainability and costs. *J. Archit. Eng.* 23:05017002. doi: 10.1061/(ASCE)AE.1943-5568.0000252

Elshafei, G., Katunský, D., Zeleňáková, M., and Negm, A. (2022). Opportunities for using analytical hierarchy process in green building optimization. *Energies* 15:4490. doi: 10.3390/en15124490

Farzaneh, H., Malehmirchegini, L., Bejan, A., Afolabi, T., Mulumba, A., and Daka, P. P. (2021). Artificial intelligence evolution in smart buildings for energy efficiency. *Appl. Sci.* 11:763. doi: 10.3390/app11020763

Frosch, R. A., and Gallopoulos, N. E. (1989). Strategies for manufacturing. *Sci. Am.* 261, 144–152. doi: 10.1038/scientificamerican0989-144

Funcke, S., and Bauknecht, D. (2016). Typology of centralised and decentralised visions for electricity infrastructure. *Util. Policy* 40, 67–74. doi: 10.1016/j.jup.2016.03.005

Fuerst, F., and McAllister, P. (2011). Green Noise or Green Value? Measuring the Effects of Environmental Certification on Office Property Values. *Real Estate Economics.* 39. doi: 10.1111/j.1540-6229.2010.00286.x

Geissdoerfer, M., Savaget, P., Bocken, N. M. P., and Hultink, E. J. (2017). The circular economy – A new sustainability paradigm? *J. Clean. Prod.* 143, 757–768. doi: 10.1016/j.jclepro.2016.12.048

Gillott, C., Mihkelson, W., Lanau, M., Cheshire, D., and Densley Tingley, D. (2023). Developing regenerate: A circular economy engagement tool for the assessment of new and existing buildings. *J. Ind. Ecol.* 27, 423–435. doi: 10.1111/jiec.13377

Goulden, M., Bedwell, B., Rennick-Egglestone, S., Rodden, T., and Spence, A. (2017). Smart grids, smart users? The role of the user in demand side management. *Energy Research & Social Science* 30, 21–29. doi: 10.1016/j.erss.2014.04.008

Greenhalgh, T., Thorne, S., and Malterud, K. (2018). Time to challenge the spurious hierarchy of systematic over narrative reviews? *Eur. J. Clin. Investig.* 48:e12931. doi: 10.1111/eci.12931

Habibi, A., and Kahe, N. (2024). Evaluating the role of green infrastructure in microclimate and building energy efficiency. *Buildings* 14:825. doi: 10.3390/buildings14030825

Hafez, F. S., Sa'di, B., Safa-Gamal, M., Taufiq-Yap, Y. H., Alrifaey, M., Seyedmahmoudian, M., et al. (2023). Energy efficiency in sustainable buildings: A systematic review with taxonomy, challenges, motivations, methodological aspects, recommendations, and pathways for future research. *Energ. Strat. Rev.* 45:101013. doi: 10.1016/j.esr.2022.101013

Hager, I., Golonka, A., and Putanowicz, R. (2016). 3D printing of buildings and building components as the future of sustainable construction? *Proc. Eng.* 151, 292–299. doi: 10.1016/j.proeng.2016.07.357

Hauge, Å. L., Thomsen, J., and Berker, T. (2011). User evaluations of energy efficient buildings: literature review and further research. *Adv. Build. Energy Res.* 5, 109–127. doi: 10.1080/17512549.2011.582350

Hensen, J. L. M., and Lamberts, R. (2011). Building Performance Simulation for Design and Operation. London: Spon Press. doi: 10.4324/9780203891612

Himeur, Y., Alsalemi, A., Al-Kababji, A., Bensaali, F., and Amira, A. (2020). Data fusion strategies for energy efficiency in buildings: overview, challenges and novel orientations. *Inf. Fusion* 64, 99–120. doi: 10.1016/j.inffus.2020.07.003

Himeur, Y., Alsalemi, A., Al-Kababji, A., Bensaali, F., Amira, A., Sardianos, C., et al. (2021). A survey of recommender systems for energy efficiency in buildings: principles, challenges and prospects. *Inf. Fusion* 72, 1–21. doi: 10.1016/j.inffus.2021.02.002

Hobson, B. W., Gunay, H. B., Ashouri, A., and Newsham, G. R. (2020). Clustering and motif identification for occupancy-centric control of an air handling unit. *Energ. Buildings* 223:110179. doi: 10.1016/j.enbuild.2020.110179

Horne, R. (2017). Housing sustainability in low carbon cities. London: Routledge.

Huang, W., and Xu, W. (2009). Interior Color Preference Investigation Using Interactive Genetic Algorithm. *Journal of Asian Architecture and Building Engineering* 8, 439–445. doi: 10.3130/jaabe.8.439

Huang, J., Hao, T., Wang, Y., and Jones, P. (2022). A street-scale simulation model for the cooling performance of urban greenery: evidence from a high-density city. *Sustain. Cities Soc.* 82:103908. doi: 10.1016/j.scs.2022.103908

International Energy Agency. (2022). Federal Subsidy for efficient buildings (BEG) by KfW. Available online at: https://www.iea.org/policies/14957-federal-subsidy-for-efficient-buildings-beg-by-kfw (Accessed December 22, 2024).

Invidiata, A., Lavagna, M., and Ghisi, E. (2018). Selecting design strategies using multi-criteria decision making to improve the sustainability of buildings. *Build. Environ.* 139, 58–68. doi: 10.1016/j.buildenv.2018.04.041

Jaffar Abass, P., and Muthulingam, S. (2025). Incorporation of phase change materials into building materials and envelopes for thermal comfort and energy optimization: A comprehensive review. *J. Build. Eng.* 103:112106. doi: 10.1016/j.jobe.2025.112106

Jaradat, M., Al Majali, H., Bendea, C., Bungau, C. C., and Bungau, T. (2023). Enhancing energy efficiency in buildings through PCM integration: A study across different climatic regions. *Buildings* 14:40. doi: 10.3390/buildings14010040

Jones, J., York, J. G., Vedula, S., Conger, M., and Lenox, M. (2019). The collective construction of green building: industry transition toward environmentally beneficial practices. *Acad. Manag. Perspect.* 33, 425–449. doi: 10.5465/amp.2017.0031

Kharbouch, Y., Mimet, A., and El Ganaoui, M. (2017). Thermal impact study of a bio-based wall coupled with an inner PCM layer. *Energy Procedia* 139, 10–15. doi: 10.1016/j.egypro.2017.11.165

Kibert, C. J., and Fard, M. M. (2012). Differentiating among low-energy, low-carbon and net-zero-energy building strategies for policy formulation. *Build. Res. Inf.* 40, 625–637. doi: 10.1080/09613218.2012.703489

Kotsopoulos, D. (2022). Organizational energy conservation matters in the Anthropocene. *Energies* 15:8214. doi: 10.3390/en15218214

Kumar, G. M. S., and Cao, S. (2021). State-of-the-art review of positive energy building and community systems. *Energies* 14:5046. doi: 10.3390/en14165046

Lamrani, B., Johannes, K., and Kuznik, F. (2021). Phase change materials integrated into building walls: an updated review. *Renew. Sust. Energ. Rev.* 140:110751. doi: 10.1016/j.rser.2021.110751

Le, D. L., Salomone, R., and Nguyen, Q. T. (2023). Circular bio-based building materials: A literature review of case studies and sustainability assessment methods. *Build. Environ.* 244:110774. doi: 10.1016/j.buildenv.2023.110774

Lee, E. S., Matusiak, B. S., Geisler-Moroder, D., Selkowitz, S. E., and Heschong, L. (2022). Advocating for view and daylight in buildings: next steps. *Energ. Buildings* 265:112079. doi: 10.1016/j.enbuild.2022.112079

Li, S., Liu, L., and Peng, C. (2020). Energy strategy pattern for climate responsive architecture: workflow in the early stages of design. *Architectural Science Review* 63, 494–506. doi: 10.1080/00038628.2020.1724071

Lieder, M., and Rashid, A. (2016). Towards circular economy implementation: A comprehensive review in context of manufacturing industry. *J. Clean. Prod.* 115, 36–51. doi: 10.1016/j.jclepro.2015.12.042

Lin, B., and Chen, Z. (2022). Net zero energy building evaluation, validation and reflection–A successful project application. *Energ. Buildings* 261:111946. doi: 10.1016/j.enbuild.2022.111946

Liu, X., and Wu, Y. (2022). Numerical evaluation of an optically switchable photovoltaic glazing system for passive daylighting control and energy-efficient building design. *Build. Environ.* 219:109170. doi: 10.1016/j.buildenv.2022.109170

Lu, Y., Khan, Z. A., Alvarez-Alvarado, M. S., Zhang, Y., Huang, Z., and Imran, M. (2020). A critical review of sustainable energy policies for the promotion of renewable energy sources. *Sustain. For.* 12:5078. doi: 10.3390/su12125078

Mahmood, N. S., Ajmi, A. A., Sarip, S. B., Kaidi, H. M., Jamaludin, K. R., and Talib, H. H. A. (2022). Modeling the sustainable integration of quality and energy management in power plants. *Sustain. For.* 14:2460. doi: 10.3390/su14042460

Mao, S., and Cao, W.-J. (2025). Evaluating material passports for circularity in the construction industry. *Sustainable Prod. Consumption* 54, 88–101. doi: 10.1016/j.spc.2024.12.021

Markou, I., Sinnott, D., and Thomas, K. (2025). Current methodologies of creating material passports: A systematic literature review. *Case Stud. Constr. Mater.* 22:e04267. doi: 10.1016/j.cscm.2025.e04267

Mavakala, B., Mulaji, C., Mpiana, P., Elongo, V., Otamonga, J. P., and Biey, E., … & Giuliani, G. (2017). Citizen sensing of solid waste disposals: crowdsourcing as tool supporting waste management in a developing country. In *Proceedings Sardinia*.

McDonough, W., and Braungart, M. (2002). Cradle to Cradle: Remaking the Way We Make Things. New York, NY: North Point Press. doi: 10.1017/S1466046609990494

Mnasri, F., El Ganaoui, M., Khelifa, M., and Gabsi, S. (2017). Aan example of feasibility study of eco materials production chain and bio-based products for eco-construction/renovation in the named greater region (Belgium, France, Luxembourg). *Energy Procedia* 139, 167–172. doi: 10.1016/j.egypro.2017.11.191

Mushtaha, E., Salameh, T., Kharrufa, S., Mori, T., Aldawoud, A., Hamad, R., et al. (2021). The impact of passive design strategies on cooling loads of buildings in temperate climate. *Case Studies in Thermal Engineering* 28:101588. doi: 10.1016/j.csite.2021.101588

Nisar, Q. A., Haider, S., Ali, F., Gill, S. S., and Waqas, A. (2024). The role of green HRM on environmental performance of hotels: mediating effect of Green Self-Efficacy & Employee Green Behaviors. *J. Qual. Assur. Hosp. Tour.* 25, 85–118. doi: 10.1080/1528008X.2022.2109235

Ntasiou, M., and Andreou, E. (2017). The standard of industrial Symbiosis. Environmental criteria and methodology on the establishment and operation of industrial and business parks. *Procedia Environ. Sci.* 38, 744–751. doi: 10.1016/j.proenv.2017.03.157

Ofgem. (2023). Great British insulation scheme. Available online at: https://www.ofgem.gov.uk/environmental-and-social-schemes/great-british-insulation-scheme

Olatunde, T. M., Okwandu, A. C., Akande, D. O., and Sikhakhane, Z. Q. (2024). Energy efficiency in architecture: strategies and technologies. *Open Access Res. J. Multidiscip. Stud.* 7, 031–041. doi: 10.53022/oarjms.2024.7.2.0024

Parker, J., Fletcher, M., Thomas, F., Miles-Shenton, D., Brooke-Peat, M., and Johnston, D., … & Glew, D. (2021). Demonstration of energy efficiency potential; literature review of benefits and risks in domestic retrofit practice and modelling.

Rajput, S., and Singh, S. P. (2019). Connecting circular economy and industry 4.0. *Int. J. Inf. Manag.* 49, 98–113. doi: 10.1016/j.ijinfomgt.2019.03.002

Rios, F. C., Panic, S., Grau, D., Khanna, V., Zapitelli, J., and Bilec, M. (2022). Exploring circular economies in the built environment from a complex systems perspective: A systematic review and conceptual model at the city scale. *Sustain. Cities Soc.* 80:103411. doi: 10.1016/j.scs.2021.103411

Ruparathna, R., Hewage, K., and Sadiq, R. (2016). Improving the energy efficiency of the existing building stock: A critical review of commercial and institutional buildings. *Renew. Sust. Energ. Rev.* 53, 1032–1045. doi: 10.1016/j.rser.2015.09.084

Sachs, J. D. (2015). The age of sustainable development. New York: Columbia University Press.

Sangadji, S., Wiktor, V., Jonkers, H., and Schlangen, E. (2017). The use of Alkaliphilic Bacteria-based repair solution for porous network concrete healing mechanism. *Proc. Eng.* 171, 606–613. doi: 10.1016/j.proeng.2017.01.387

Sathaye, J., Lucon, O., Rahman, A., Christensen, J., Denton, F., Fujino, J., et al. (2011). "Renewable energy in the context of sustainable development" in IPCC special report on renewable energy sources and climate change mitigation. eds. O. Edenhofer, R. Pichs-Madruga, Y. Sokona, K. Seyboth, P. Matschoss and S. Kadneret al. (Cambridge, United Kingdom and New York, NY, USA: Cambridge University Press).

Sebestyén, V. (2021). Renewable and sustainable energy reviews: environmental impact networks of renewable energy power plants. *Renew. Sust. Energ. Rev.* 151:111626. doi: 10.1016/j.rser.2021.111626

Shree, V., Dwivedi, A., Saxena, A., Pathak, S. K., Agrawal, N., Tripathi, B. M., et al. (2025). A comprehensive review of harnessing the potential of phase change materials (PCMs) in energy-efficient building envelopes. *J. Build. Eng.* 101:111841. doi: 10.1016/j.jobe.2025.111841

Statista (2023). Statista – the statistics portal for market data, market research and market studies: 2023 in numbers | Statista

Sun, Y., Wilson, R., Liu, H., and Wu, Y. (2021). Numerical investigation of a smart window system with thermotropic parallel slat transparent insulation material for building energy conservation and daylight autonomy. *Build. Environ.* 203:108048. doi: 10.1016/j.buildenv.2021.108048

Tonellato, G., Kummert, M., Candanedo, J., Beaudry, G., and Pasquier, P. (2025). A model-based continuous commissioning method for an efficient integration of ground source heat pumps in the building ecosystem. *Energ. Buildings* 333:115492. doi: 10.1016/j.enbuild.2025.115492

U.S. Environmental Protection Agency. (2022). Summary of inflation reduction act provisions related to renewable energy. Available online at: https://www.epa.gov/green-power-markets/summary-inflation-reduction-act-provisions-related-renewable-energy (Accessed November 17, 2024).

Ürge-Vorsatz, D., Khosla, R., Bernhardt, R., Chan, Y. C., Vérez, D., Hu, S., et al. (2020). Advances toward a net-zero global building sector. *Annu. Rev. Environ. Resour.* 45, 227–269. doi: 10.1146/annurev-environ-012420-045843

Van Ewijk, S., Ashton, W. S., Berrill, P., Cao, Z., Chertow, M., and Chopra, S. S. (2023) 10 insights from industrial ecology for the circular economy. (u.å.). [Dataset].

Vink, K., and Vinke-de Kruijf, J. (2024). The impacts of urban green infrastructure on water and energy resources: lessons from and the need for integrated studies. Monteiro, I. C. M., Santos, C., Matos, C., and Sá, A. B. (red.), Sustainable development (Vol. 25). IntechOpen, London

Wags, N. D., and Ifeanyi, O. E. (2024). A comprehensive review of building energy management systems (BEMS) for improved efficiency. *World J. Adv. Res. Rev.* 21, 829–841. doi: 10.30574/wjarr.2024.21.3.0746

Wang, J., and Banzhaf, E. (2018). Towards a better understanding of green infrastructure: A critical review. *Ecol. Indic.* 85, 758–772. doi: 10.1016/j.ecolind.2017.09.018

Wang, N., Phelan, P. E., Gonzalez, J., Harris, C., Henze, G. P., Hutchinson, R., et al. (2017). Ten questions concerning future buildings beyond zero energy and carbon neutrality. *Build. Environ.* 119, 169–182. doi: 10.1016/j.buildenv.2017.04.006

Weinand, J. M., Scheller, F., and McKenna, R. (2020). Reviewing energy system modelling of decentralized energy autonomy. *Energy* 203:117817. doi: 10.1016/j.energy.2020.117817

Wiktor, V., and Jonkers, H. M. (2011). Quantification of crack-healing in novel bacteria-based self-healing concrete. *Cem. Concr. Compos.* 33, 763–770. doi: 10.1016/j.cemconcomp.2011.03.012

Williams, B., Bishop, D., Gallardo, P., and Chase, J. G. (2023). Demand side management in industrial, commercial, and residential sectors: a review of constraints and considerations. *Energies* 16:5155. doi: 10.3390/en16135155

Yu, S., Wang, S., Cheng, X., and Li, L. (2024). Green finance and total factor energy efficiency: theoretical mechanisms and empirical tests. *Front. Environ. Sci.* 12:1399056. doi: 10.3389/fenvs.2024.1399056

Zaniboni, L., and Albatici, R. (2022). Natural and mechanical ventilation concepts for indoor comfort and well-being with a sustainable design perspective: A systematic review. *Buildings* 12:1983. doi: 10.3390/buildings12111983

Zhao, C., Zhang, W., Zhang, M., and Zhang, C. (2021). Energy saving construction technology analysis of building engineering. *IOP Conference Series: Earth and Environmental Science* 676:012026. doi: 10.1088/1755-1315/676/1/012026