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Editorial

# Sustainability in Energy and Buildings: Future Perspectives and Challenges

**Camilla Lops** * and **Sergio Montelpare**

Department of Engineering and Geology, University "G. d'Annunzio" of Chieti-Pescara, 65122 Pescara, Italy; sergio.montelpare@unich.it
* Correspondence: camilla.lops@unich.it; Tel.: +39-085-453-7258

How can we make the built environment more energy-efficient, sustainable, and resilient? This fundamental question has emerged as a critical priority for researchers, policymakers, and practitioners worldwide as the urgency of climate action intensifies. Buildings represent one of the most significant contributors to global energy consumption and greenhouse gas (GHG) emissions, accounting for approximately 32% of global energy demand and 34% of $CO_2$ emissions, with operational emissions reaching a record of 9.8 Gt and embodied carbon recorded at approximately 2.9 Gt in 2023 [1]. Specifically, in the European Union, buildings consume nearly 40% of total energy and contribute to approximately 36% of energy-related emissions [2,3]; similar patterns have emerged across developed economies globally. In rapidly urbanizing regions such as the Asia-Pacific and Sub-Saharan Africa, where urban populations are projected to double by 2050, the environmental impact from new construction and infrastructure development poses significant challenges for global emission reduction targets without coordinated sustainable building practices [4].

The scale and pervasive impact of buildings make them central to both challenges and opportunities arising from global sustainability transitions. Beyond their substantial environmental footprint, buildings fundamentally shape urban quality of life, influencing thermal comfort, indoor air quality, health outcomes, and community resilience to climate extremes [5,6]. This dual role positions the built environment as a unique platform for achieving co-benefits: reducing emissions while simultaneously enhancing human well-being and urban livability. International frameworks such as the Paris Agreement and the United Nations (UN) Sustainable Development Goals (SDGs) explicitly recognize buildings as critical points of intervention for climate mitigation and adaptation [7].

Contemporary buildings offer substantial opportunities for energy reduction through optimized envelope performance, renewable energy integration, and intelligent management systems, with leading examples demonstrating potential energy savings of 75–90% compared to their conventional counterparts [8,9]. However, despite technological advances and growing policy support, many existing building approaches continue to face significant limitations in achieving comprehensive sustainability. Current retrofit practices typically address only 30–40% of buildings' improvement potential, while new construction often falls short of net-zero targets due to cost constraints and regulatory gaps [10,11]. These limitations in scalability, affordability, and whole life cycle integration restrict broader adoption across diverse economic contexts, from developed markets to emerging economies, where rapid urbanization demands immediate solutions.

Overcoming these persistent barriers requires systemic approaches that extend beyond individual technologies to encompass holistic planning methodologies, supportive

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policy frameworks, innovative financing mechanisms, and unprecedented cross-sector collaboration. The transition toward a sustainable built environment demands integration across disciplines (from architectural design and engineering systems to urban planning, behavioral science, and circular economy principles) while addressing the diverse needs of global communities facing varying climatic, economic, and social conditions.

In response to these global demands, research in recent years has dramatically intensified its focus on advancing building technologies, design strategies, and management systems that can transform the built environment from an energy consumer into a driver of sustainability. The scale of this transformation is evident in market projections: the global smart building market was valued at USD 117.4 billion in 2024 and is projected to register a Compound Annual Growth Rate (CAGR) of approximately 21% until 2032 [12]. This rapid expansion reflects a fundamental shift in the construction industry toward sustainable practices across developed and emerging economies worldwide.

Contemporary research has increasingly converged on several transformative areas of innovation, with smart building materials leading the charge. These advanced materials are designed to promptly respond to environmental stimuli such as temperature, stress, and humidity, thereby enhancing both performance and resilience [13]. Notable examples include phase-change materials (PCMs) that regulate thermal conditions, self-healing concrete that extends structural durability, and shape-memory alloys that enable adaptive building components [14–17].

Advanced façade systems represent a dynamic frontier of innovation, combining responsive glazing technologies, building-integrated photovoltaics, and biomimetic designs that adapt to local climatic conditions while simultaneously maximizing daylight availability and ensuring thermal comfort [18–20]. In parallel, nature-based solutions (NbSs) are gaining unprecedented momentum in global building and urban practices, with applications ranging from green roofs and living walls to natural ventilation, rainwater harvesting, and urban biodiversity integration [21]. These approaches not only enhance building performance but also provide critical ecosystem services, such as improved air quality and mitigation of the urban heat island effect [22–24]. Complementing these strategies, circular economy (CE) principles are increasingly embedded in sustainable building design, encouraging material reuse, design for disassembly, and waste reduction across the construction life [25]. By prioritizing local sourcing and resource efficiency, these principles reduce transportation-related emissions while strengthening regional economies, creating a more resilient and regenerative built environment [26,27].

Building upon these approaches, life cycle assessment (LCA) methodologies have evolved into comprehensive frameworks (such as prospective life cycle assessment—pLCA) that evaluate impacts from material extraction through end-of-life disposal while also accounting for future scenarios, thus enabling evidence-based decision-making that optimizes both environmental performance and economic viability [28]. This holistic perspective extends well beyond traditional energy efficiency metrics to encompass embodied carbon, water consumption, material toxicity, and even social equity considerations. Consequently, buildings are increasingly envisioned not merely as minimized sources of environmental impact but as active contributors to regenerative urban systems, all while maintaining economic competitiveness across diverse global contexts, from established economies to rapidly urbanizing regions.

Finally, the application of artificial intelligence (AI) has emerged as a particularly promising frontier for advancing the sustainability of buildings and infrastructure. Its integration into energy optimization represents a critical pathway for reducing emissions. Recent studies suggest that, when combined with appropriate policy measures, AI could lower building energy use and associated emissions by as much as 40–90% by 2050, while more conservative estimates indicate reductions of 8–19% through automated design processes, predictive maintenance, and intelligent HVAC control systems [29–31]. Beyond direct energy efficiency, AI is also transforming the performance of renewable energy systems by enhancing forecasting accuracy and operational productivity [32]. AI-driven predictive analytics and monitoring tools have been shown to improve system uptime by 15–20% through early fault detection, translating into annual cost savings of approximately USD 10,000–30,000 per MW of installed capacity [33]. Furthermore, machine learning (ML) algorithms can optimize the interaction between smart building materials and environmental conditions; through this, they enable a more efficient response to thermal loads in phase-change materials and simultaneously coordinate with adaptive facade systems to minimize energy consumption while maximizing occupant comfort.

The studies presented in this Special Issue collectively reflect these innovative pathways, offering a broad range of approaches that demonstrate not only theoretical advances but also practical applications for the building industry. Their findings illustrate how emerging technologies can enhance performance while aligning with clean-label requirements and sustainability certification schemes. Importantly, they highlight the need for research that extends beyond isolated prototypes to consider large-scale deployment and long-term viability.

Future research should therefore prioritize the development of scalable implementation strategies for advanced sustainability technologies in both new construction and existing building retrofits, ensuring cost-effectiveness while maintaining performance standards. Attention must also be directed toward assessing the durability and long-term performance of integrated building systems, investigating user acceptance and market adoption, particularly for technologies with significant upfront costs or operational shifts, and rigorously evaluating the environmental benefits of sustainable building practices, including their potential contributions to global climate mitigation.

Regarding future outlook, the research findings highlighted in this volume clearly point toward several emerging directions. The path ahead will increasingly involve the integration of digital intelligence, advanced materials, and systemic sustainability frameworks, all of which are central to shaping resilient, low-carbon buildings and cities. We encourage researchers and practitioners to continue advancing these themes in the second volume, entitled *"Sustainability in Energy and Buildings: Future Perspectives and Challenges: 2nd Edition"*, where such topics will be at the forefront.

With continued progress in technology integration, circular economy strategies, and life cycle assessment methodologies, sustainable building practices hold immense potential to accelerate climate change mitigation, resource efficiency, and environmental protection in the built environment. Although the challenges are considerable, the opportunities are equally compelling. The contributions in this Special Issue reaffirm the vitality of the field and its essential role in driving the global transition toward sustainability.

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## Abbreviations

The following abbreviations are used in this manuscript:

| | |
|---|---|
| USD | United States dollar |
| GHG | Greenhouse gas emissions |
| UN | United Nations |
| SDG | Sustainable Development Goal |

| | |
|---|---|
| CAGR | Compound Annual Growth Rate |
| NbS | Nature-based solutions |
| CE | Circular economy |
| LCA | Life cycle assessment |
| pLCA | Prospective life cycle assessment |
| AI | Artificial intelligence |
| HVAC | Heating, ventilation, and air conditioning |
| ML | Machine learning |

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