

State-of-the-art review of urban building energy modelling on supporting sustainable development goals

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HIGHLIGHTS

- Review contributions of UBEM to SDGs and its potential for sustainability.
- Identify key gaps in UBEM's response to diverse SDG-related urban challenges.
- Expand scope of UBEM to incorporate energy equity and urban resilience.
- Provide actionable insights to align UBEM with global sustainability.

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ABSTRACT

Urban Building Energy Modelling (UBEM) is a powerful computational tool capable of trackable large-scale building energy performance assessment, enabling more effective management and optimisation of urban energy systems. While UBEM has preliminarily been engineering-oriented, this study examines its potential contributions to support the United Nations Sustainable Development Goals (SDGs). Through a systematic literature review, this work reveals that the UBEM predominantly supports the SDGs directly associated with energy and environment, namely SDGs 7, 11, 12, and 13, while contributions to other goals, such as SDGs 1, 4, 8, 9, 15, and 17, remain underexplored. Although UBEM offers transformative potential in supporting the SDGs, its impact is currently limited by geographic imbalances, methodological inconsistencies, and insufficient integration of socio-economic indicators. To address these limitations, an expanded research agenda is proposed, which integrates life-cycle assessments to capture holistic environmental impacts, collaborative open-source frameworks to improve data accessibility, and participatory approaches to ensure inclusivity in decision-making processes. By addressing these gaps, the study aims to enhance the applicability and adaptability of UBEM, allowing it to tackle a wider array of issues within SDGs. Additionally, this work underscores UBEM's potential as a transformative tool for advancing sustainable urban energy strategies, bridging technical innovation with interdisciplinary methodologies to foster equitable and resilient urban development in alignment with the 2030 Agenda for Sustainable Development.

1. Introduction

The rapid urbanisation and increasing energy consumption in cities have emerged as critical challenges in the 21st century. Urban areas currently account for approximately 75 % of global energy consumption

and 70 % of greenhouse gas emissions [1], indicating the urgent need for effective energy management strategies in urban environments. In addition to the environmental burden, poor energy performance in urban areas contributes to energy poverty, limited access to thermal comfort, and increased vulnerability to climate risks [2,3]. These challenges directly affect public health, social equity, and economic

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Nomenclature

BIM	Building Information Modelling
ESG	Environmental, Social, and Governance
GIS	Geographic Information System
LiDAR	Light Detection and Ranging
NDCs	Nationally Determined Contributions
SDGs	Sustainable Development Goals
SLR	Systematic Literature Review
UBEM	Urban Building Energy Modelling

resilience. As cities adopt ambitious goals for carbon neutrality, climate adaptation, and just energy transitions [4], there is an increasing demand for tools that can evaluate the impacts of energy strategies at the scale of neighbourhoods or entire districts. In response to these challenges, Urban Building Energy Modelling (UBEM) emerges as a practical and scalable approach for understanding and optimising building energy performance at the urban level. It enables the simulation of spatial energy patterns, assessment of retrofit scenarios, and evaluation of policy interventions, making it highly relevant for decision-making in sustainable urban planning.

1.1. Overview of UBEM

UBEM emerged approximately a decade ago as a response to the increasing demand for comprehensive energy analyses at the urban scale, extending beyond the scope of individual building simulations. This term, UBEM, was first formally defined by Reinhart and Cerezo Davila [5] as a computational framework for simulating the energy performance of buildings at district and city scales through bottom-up physics-based methods. Its appearance marks a remarkable shift from traditional single-building energy modelling to a more integrated urban-scale approach. UBEM represents a sophisticated methodology that bridges the gap between building science and urban planning as well as management, enabling energy analysis at unprecedented spatial and temporal scales. At its core, UBEM creates virtual representations of urban building stocks by synthesising various data streams, from Geographic Information System (GIS) data, Light Detection and Ranging (LiDAR) surveys, and tax assessment databases, to weather conditions, occupancy patterns, and building systems, ultimately generating comprehensive city-scale energy insights [6]. This systematic approach enables both the assessment of current energy use and the prediction of outcomes in buildings and their systems after modification, thereby serving as a powerful decision-making tool for achieving low-energy cities through various energy and carbon reduction strategies [7].

To implement this capable modelling approach and realise its potential for urban policy decision-making, considerable scholarly efforts have been devoted to developing UBEM platforms over the past decade. Several well-established platforms have emerged, each with distinct features and capabilities. City Energy Analyst, founded by Swiss Federal Institute of Technology Zurich, an open-source urban building energy simulation platform, integrates urban planning and energy systems engineering to analyse building energy consumption, energy infrastructure planning, and low-carbon city design [8]. CityBES, from Lawrence Berkeley National Laboratory, focuses on retrofit analysis and energy conservation measures [9]. CitySim, developed by École Polytechnique Fédérale de Lausanne, specialises in simulating solar radiation and building thermal interactions [10]. UMI, created by the Massachusetts Institute of Technology, excels in neighbourhood-scale analysis and seamlessly integrates with design software [11]. These platforms, either mechanistic white-box models or reduced-order grey-box models, primarily designed for urban building cluster performance simulation, typically generate quantitative outputs, including hourly energy

consumption profiles, peak demand predictions, retrofit potential assessments, and carbon emission calculations. A more detailed summary of the established UBEM platform can be found in Table A1 in Appendix A.

While much of the development of these platforms has taken place within academic and technical circles, UBEM is increasingly being applied in real-world planning and policy contexts. In the United States, ComStock, developed by the Department of Energy, provides national-scale simulations of non-domestic buildings that underpin policy testing and utility demand forecasting [12]. In the United Kingdom, outputs from the National Buildings Database have supported carbon budgeting and non-domestic retrofit programmes [13]. In Europe, the TABULA project has helped define domestic archetypes and inform cross-national energy efficiency [14]. These examples demonstrate that UBEM is already shaping regulatory thinking and investment strategies in a growing number of institutional settings, although adoption remains uneven and highly dependent on data availability and administrative capacity.

Recognising the growing interest in UBEM, several reviews have also summarised advancements and trends in this field. Excell et al. [15] showcased how integrating data-driven techniques with simulation-based frameworks can unravel the complexities of multi-scale retrofitting, offering insights into thermal comfort enhancement. By mapping research trends through bibliometric methods, Salvalai et al. [16] identified foundational concepts and emerging simulation methodologies that shape the UBEM domain. Another piece of work introduced the minimum viable UBEM framework, which simplifies data and computational requirements, making targeted urban energy modelling more accessible [6]. Ali et al. [17] dissected the strengths, limitations, and opportunities within existing UBEM methods, providing a structured approach for resource-efficient urban energy planning. Ferrando et al. [18] critically compared bottom-up physics-based tools, highlighting disparities in analytical precision, input demands, and workflow usability, while calling for greater standardisation in UBEM practices. There are many more reviews summarising the UBEM technology path from different perspectives, including the ways of augmenting model input data [19–21], differences in modelling in specific climatic regions [22,23], calibration of model performance [24], integration of machine learning [25], etc., which are not repeated here. Collectively, these reviews offer in-depth technical comparisons, covering categories such as modelling approaches, and topics including interoperability, scalability, uncertainty analysis and validation, yet they also reveal notable limitations. The predominance of technical and quantitative outputs in UBEM-related studies often sidelines broader dimensions, leaving the capacity of such studies to address diverse requirements underexplored. Existing big-scale building modelling research frameworks, especially UBEM, tend to overlook the comprehensive explorations of impacts on critical social challenges [26]. Examples of these social challenges include energy poverty [27], housing affordability [28], community acceptance of energy interventions [29], and equitable access to energy efficiency improvements [30]. This observation leads to the first research gap in this study as the absence of systematic analysis on how UBEM can address broader sustainability needs encompassing social equity, economic inclusion and community resilience in addition to environmental performance.

1.2. UBEM and sustainable development goals

Urban sustainability challenges are increasingly being addressed within established international and national policy frameworks, such as the Paris Agreement [31], the United Nations New Urban Agenda [32], and Nationally Determined Contributions (NDCs) [33]. These frameworks set quantitative targets for emissions reduction, resilience building, and equitable access to energy, requiring robust analytical tools to guide planning and monitor progress. Within this policy landscape, UBEM serves as a decision-support instrument that links building

science with urban governance. By producing high-resolution spatial and temporal profiles of energy demand and supply, UBEM provides quantitative evidence that can be directly aligned with climate action plans, municipal carbon budgets, and energy equity metrics [15,34]. In this role, it addresses not only the technical dimension of energy performance but also policy-relevant priorities such as reducing vulnerability, enhancing resilience, and accelerating low-carbon transitions [26].

Given the multi-dimensional nature of these objectives, a consistent framework is needed to evaluate UBEM's potential contributions in a way that integrates environmental, social, and economic dimensions. The United Nations Sustainable Development Goals (SDGs), adopted in 2015 as part of the 2030 Agenda for Sustainable Development, present an internationally recognised framework that encompasses both environmental and social dimensions of sustainable development [35], offer such a framework by defining specific targets and indicators that enable systematic assessment of progress toward sustainable development across multiple domains. The SDGs comprise 17 integrated goals addressing global challenges, providing specific targets and indicators that enable systematic assessment of progress toward sustainable development across social, economic and environmental dimensions. Before detailing how the SDGs can offer such an integrated lens, it is essential to review the extent to which recent UBEM studies have already attempted to embed socio-economic or equity metrics.

UBEM has begun to move beyond purely technical diagnostics toward more inclusive, cross-sector assessments. For instance, Heidelberg and Rakha [36] enriched domestic archetypes with census variables, including income, tenure and household size, to reveal retrofit scenarios that would otherwise overlook low-income groups. Ang et al. [37] used smart-meter analytics to generate hourly load profiles for distinct "socio-economic personas", showing that ignoring income heterogeneity can bias city-wide demand estimates by up to 10 %. Cong et al. [38] proposed the energy equity gap, a relative metric that captures hidden energy poverty not flagged by conventional income statistics. Recent studies have also begun to operationalise the "social" dimension of UBEM through explicit, quantitative metrics. Tong et al. [39] employed Lorenz curves and a building-energy Gini coefficient to quantify inequality in energy use intensity across race and income defined neighbourhoods. Also, a recent heat-vulnerability study combines UBEM-derived indoor heat indices with census-based social-vulnerability scores to produce spatial thermal inequity maps [40]. Ayyagari et al. [41] proposed the Hours-of-Safety (HOS) metric, which is the number of hours a dwelling keeps indoor temperatures within clinically safe bounds during a power outage, and use UBEM simulations to compare pre-1950, code-compliant and Passive-House archetypes. These developments demonstrate that UBEM is no longer confined to technical diagnostics but is increasingly contributing to policy-relevant objectives. The ability to integrate spatially and temporally resolved evidence with measures of equity, vulnerability and resilience positions UBEM as a valuable tool for supporting internationally recognised sustainability goals. In this context, the SDGs provide a coherent framework that translates broad policy ambitions into specific and measurable targets and indicators, offering a consistent basis for evaluating UBEM's contributions across environmental, social and economic dimensions. For example, the methodological strands of UBEM can be explicitly aligned with specific SDG targets and indicators. One example is that physics-based simulation can support SDG 13 by quantifying the potential for emissions reduction under different retrofit and electrification pathways. Another example is that data driven socio-technical modelling can contribute to SDG 7 by identifying underserved populations. Establishing these links provides a structured basis for connecting modelling choices with measurable sustainability outcomes and for situating UBEM within recognised policy frameworks.

In the following, it is therefore needed to examine how the SDGs have been leveraged in allied building-modelling domains and why a similar mapping is overdue for UBEM. Currently, the SDGs framework

has already been employed in various building modelling related reviews, demonstrating its utility in analysing the various implications in this specific domain. For example, Liu et al. [42] developed an innovative framework integrating Building Information Modelling (BIM) and smart city technologies to address urban sustainability challenges, demonstrating noteworthy contributions to SDG 8 (Decent Work and Economic Growth) and SDG 17 (Partnerships for the Goals) through enhanced resource management and stakeholder collaboration. Jing and Alias [43] proposed a theoretical framework combining BIM with Environmental, Social, and Governance (ESG) criteria, which optimises resource efficiency, reduces carbon emissions, and supports the achievement of SDG 11 (Sustainable Cities and Communities) and SDG 13 (Climate Action) across the building life-cycle. Additionally, Regona et al. [44] conducted a systematic literature review on artificial intelligence in the construction industry, identifying its transformative role in optimising energy efficiency, sustainable urban infrastructure, and inclusive cities, thus contributing directly to SDG 7 (Affordable and Clean Energy), SDG 9 (Industry, Innovation, and Infrastructure), and SDG 11. Furthermore, Scrucca et al. [45] employed life cycle assessment to evaluate the sustainability performance of buildings, providing quantitative insights into their contributions to SDGs by reducing environmental impacts and enhancing climate resilience.

These applications highlight the framework's effectiveness in bridging technical assessments with broader outcomes, offering the potential of the SDGs framework to be applied to exam the wider impacts of UBEM. However, the potential for systematic integration between UBEM research and comprehensive SDG-based analysis framework remains unexplored, particularly given the great capacity of UBEM studies to address key sustainability challenges outlined in the SDGs. This misalignment defines the second critical research gap in this study as the lack of a review that systematically integrates UBEM with comprehensive multidimensional analytical frameworks such as the SDGs. Without such integration, current research remains limited in its capacity to address the interconnected challenges of social equity, economic development, and environmental sustainability. Here these three challenges refer to ensuring inclusive decision-making, balancing growth with equitable resource use, and protecting natural systems within planetary boundaries while addressing systemic trade-offs and interconnections [46].

1.3. Objective of this study

To address the abovementioned two research gaps, which are limited exploration of UBEM's broader sustainability applications and the absence of a comprehensive review linking UBEM with multidimensional frameworks such as the SDGs, this work reviews UBEM studies from the SDGs perspective, with particular attention to implications that extend beyond purely technical considerations. Although a technical review and classification of UBEM methodologies is important for the development of the field, this paper does not aim to provide such an exhaustive survey because numerous detailed reviews already exist, as discussed in previous subsection 1.1. Meanwhile, as a review paper, it is essential to analyse future research trends in UBEM's applications to support SDGs based on existing literature. In light of the discussion above and to address the two identified research questions, whilst facilitating the future development of UBEM research, this study proposes three research questions below accordingly.

- What are the current limitations of UBEM in responding to extended sustainability requirements?
- How do existing UBEM studies align with SDGs, and what are their gaps in addressing social, economic and environmental challenges?
- What methodological modifications and innovations are needed to enhance the capacity of UBEM to address the wider sustainability targets?

The rest of this review is structured as follows. Section 2 sketches the criteria for the inclusion of literature in this paper. Section 3 provides a descriptive analysis of the selected papers. Section 4 conducts comprehensive analyses of the selected literature by different SDG objectives. Section 5 details the current state of existing UBEM responses to various challenges, as well as future challenges and potential research directions for UBEM research. Section 6 wraps up this study.

2. Review methodology

This research employs a Systematic Literature Review (SLR) methodology, adhering to the latest 2020 PRISMA guidelines [47], to comprehensively examine UBEM-related studies published in prominent academic journals. The SLR is conducted in two phases, comprising article selection and content analysis. During the article selection phase, considering the prominence of UBEM and the varying quality of UBEM-related research, the authors focus exclusively on peer-reviewed journal articles to ensure the validity and credibility of research findings. Conference proceedings, book chapters, and other sources are excluded. As the term UBEM first appeared in the study by Reinhart and Cerezo Davila [5] in 2016, it is considered a specific term for this research domain. Therefore, “Urban Building Energy Modelling” is directly utilised as the search keyword. The Scopus database is selected due to its established reputation and comprehensive coverage of UBEM literature. A preliminary search in Scopus confirms the feasibility of using “Urban Building Energy Modelling” as a proprietary search term, as no relevant journal articles were found before 2016. Accordingly, the temporal scope of the reviewed literature spans from the emergence of the UBEM definition in 2016 to the end of 2024. The detailed search strings and filters used for initial literature scanning are summarised in Table 1. The Scopus query returns 205 peer-reviewed journal records at the PRISMA identification stage. As the search term “Urban Building Energy Modelling” is highly specific, no articles are excluded at this stage. No duplicate items or inaccessible full texts arose, so all 205 records proceeded directly to the title–abstract screening stage. Utilising Elsevier’s 2023 SDGs mapping functionality [48] integrated within Scopus, a full-text review is conducted to filter out papers that do not address SDG-related challenges. This tool maps academic publications to the United Nations’ 17 Sustainable Development Goals through specific search queries and machine learning algorithms, enabling precise evaluation of research contributions to global sustainability objectives [48]. All 205 UBEM journal records are processed through the SDG-mapping tool, which uses curated Boolean queries and a machine-learning classifier to assign provisional SDG tags. To ensure accuracy and reduce algorithmic or interpretive bias, four reviewers independently validate each SDG assignment based on the full-text content of the articles, rather than relying solely on keyword matches or metadata. Reviewers cross-check results in pairs and collaboratively re-examine all articles with missing or ambiguous SDG tags. While formal inter-coder reliability statistics are not computed, consistency is reinforced through multiple calibration meetings and consensus-based resolution of discrepancies. The sequence, which includes automatic tagging, manual confirmation, manual rescue, yields the final set of 134 articles linked to at least one

SDG. An article is excluded if SDG-mapping tool assigns it no SDG tag, or the full text lacks sufficient information to allocate an SDG target manually, or the item constitutes a review rather than primary UBEM research. This process yields 134 primary studies, all of which enter the qualitative synthesis set out in following sections. The total workflow of the selection process is illustrated in Fig. 1. And Fig. 2 sketches the SDG-mapping workflow used in this review. Table C1 in Appendix C lists all the corresponding articles. During the content analysis phase, the 134 included studies are systematically reviewed and coded based on a structured set of variables. These include the SDG(s) addressed, geographic region, modelling scale, modelling approach, and any policy or equity-related dimensions. Coding is conducted using a shared spreadsheet template designed by the authors, and performed by four reviewers working in pairs. To ensure consistency and accuracy, the team holds calibration sessions and resolves disagreements through discussion. In summary, this review applies a structured set of inclusion and exclusion criteria to ensure methodological rigor. Eligible articles must explicitly centre on Urban Building Energy Modelling, be published in peer-reviewed journals, and be written in English. Each study must also demonstrate relevance to at least one SDG, confirmed through automated mapping and manual validation. Studies are excluded if they do not treat UBEM as a core methodological focus, lack sufficient detail to determine SDG alignment, or fall outside the scope of original journal research, such as conference papers, book chapters, or reviews.

For the purpose of this systematic review, the term state-of-the-art is defined along two complementary axes. Temporally, this study includes every peer-reviewed UBEM study published between 2016 and 2024, thereby extending the evidence base beyond earlier review. Conceptually, the study provides the first synthesis that explicitly aligns UBEM outcomes with the full set of seventeen SDGs, offering a multidimensional appraisal that spans technical advances, implementation scale and policy relevance. The label therefore signals both the up-to-date coverage of the literature and the novel SDG-centred analytical lens, rather than privileging any single modelling technique or software platform.

3. Descriptive and statistical analysis

This section provides a preliminary analysis of the chosen 134 reviewed research papers since the introduction of the UBEM concept in 2016. It begins by examining the temporal distribution of publications and research scale, followed by an analysis of the geographic focus of UBEM case studies. The section then explores the intellectual structure of the field through keyword co-occurrence analysis and concludes by identifying key thematic trends over time. Together, these descriptive insights offer a comprehensive overview of how UBEM research has developed in scope, depth, and focus over the past decade.

The evolution of UBEM research can be characterised by both its temporal growth and the scale of applications. Fig. 3 visualises how research outputs from 2016 to 2025 are distributed across different levels of analysis. Following the formal introduction of the UBEM concept in 2016, the number of related studies was initially modest, with fewer than ten papers published in both 2016 and 2017. From 2018 onwards, however, annual output increased, peaking in 2022 with over 40 publications. This upward trend aligns with global policy shifts toward carbon neutrality [49], the widespread adoption of smart city initiatives [15], and technological advancements such as the integration of urban digital twins (UDTs) into energy planning and management frameworks [50]. These developments provide both the technical infrastructure and policy incentives for expanding UBEM applications. The growing academic attention also reflects an expanding research community dedicated to advancing UBEM methodologies and their practical relevance. In addition to this growth trajectory, UBEM studies exhibit clear differences in spatial focus. UBEM-related research can be categorised based on the scale of the study, including national, regional, urban, and community levels [26]. Most studies concentrate on the city

Table 1
Search strings and filters used for initial literature scanning.

Component	Details
Database	Scopus
Search String	TITLE-ABS-KEY(“Urban Building Energy Modelling”)
Document Type	Peer-reviewed journal articles only
Filter	
Language Filter	English only
Publication Year	Limited to articles published in 2016 or later
Full Search Query	TITLE-ABS-KEY(“Urban Building Energy Modelling”) AND DOCTYPE(ar) AND LANGUAGE(english) AND PUBYEAR >2015

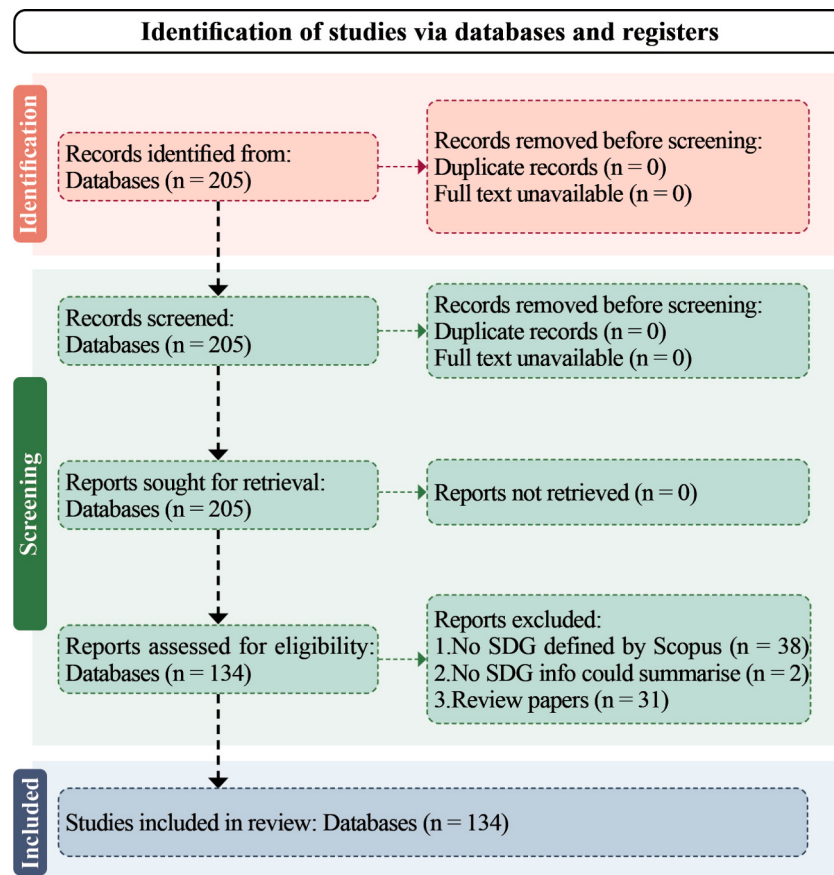


Fig. 1. Workflow of the literature scanning process following PRISMA guideline.

scale, with 68 publications addressing energy dynamics at the urban level. This focus reflects the role of cities as key sites of energy consumption and policy experimentation. Community-scale research follows with 50 studies, showing a consistent rise from 2019 onwards and signalling increased interest in equity-driven and decentralised interventions. In contrast, only nine studies are conducted at the national level and seven at the regional level, suggesting limited engagement with large-scale planning or cross-jurisdictional modelling. The remaining studies are categorised as “others”, typically representing methodological work without a defined spatial application. Taken together, the dual-axis distribution of UBE research by time and scale reveals both huge progress and persistent gaps. While recent years have seen notable advances in data availability, modelling capability, and practical relevance, especially at city and community levels, the field remains underdeveloped in national and regional contexts. Addressing this imbalance is essential for integrating UBE insights into top-down energy policy design and for enabling broader, systems-level strategies to support sustainable urban transitions.

An analysis of the spatial distributions of the selected cases in the reviewed papers shows that the current research focuses mainly on cases from North America, Europe and East Asia. Among them, the United States, China and Italy emerge as the leading contributors, with 24, 19, and 9 studies, respectively. This may be attributed to factors such as the presence of advanced research institutions, significant investment in urban energy modelling and strong policy support to combat climate change. Yet the pattern goes beyond country counts. Most of the documented cities are compact, high-density and situated in temperate or cold climates, such as Milan, Zurich, Montreal and Stockholm, where heating loads dominate and rich cadastral or utility data are available. By contrast, only a small handful of papers examine low-density conurbations or cities in tropical and arid zones, such as Mumbai, Bengaluru

or Santiago, even though these regions face the fastest growth in cooling demand. Economically, almost all study locations lie in high- or upper-middle-income countries; cases from lower-middle-income contexts remain rare, and none originate in low-income nations. This combined skew in urban typology, economic setting and climate raises questions about the transferability of current UBE methods to data-scarce, informally built or climatically extreme environments. Addressing the imbalance will require an inclusive research agenda that deliberately targets under-represented urban forms, economic contexts and climate zones so that UBE can support genuinely global progress toward the SDGs. Fig. 4 highlights these details. And the underlying case-by-case data supporting this analysis are provided in Table C1 in the appendix.

Fig. 5 visualises the keyword co-occurrence network generated from the reviewed UBE literature, offering insights into the intellectual structure and thematic evolution of the field. The map reveals several densely connected keyword clusters, each representing a thematic sub-domain. At the centre of the network, terms such as “urban building energy modeling”, “simulation”, “generation”, and “consumption” dominate in size and connectivity, reflecting their centrality in the UBE discourse. This core cluster signifies the foundational focus on energy modelling frameworks and demand estimation at the urban scale. Surrounding this core, multiple thematic communities can be identified through colour-coded groupings. The green cluster, for instance, includes “occupant behavior”, “bottom-up”, “temperature”, and “building energy modeling” highlighting the increasing attention to micro-level dynamics and behavioural patterns in urban energy simulation. The red cluster to the right features terms like “building stock modeling”, “agent-based modelling”, “efficiency”, and “thermal comfort” indicating a methodological focus on stock-level simulations, often tied to equity and performance evaluation. Another prominent cluster, shown in blue, links “optimization”, “archetypes”, and “prediction”

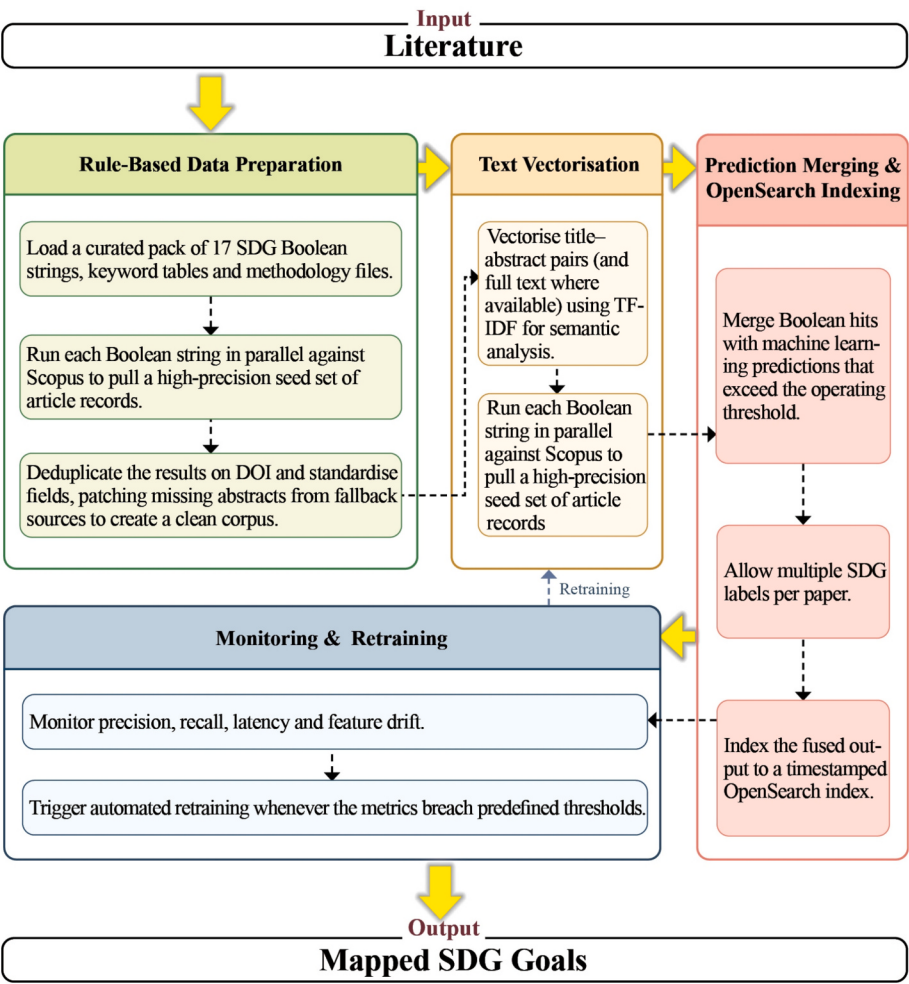


Fig. 2. Workflow of SDG-mapping tool used in this study [48].

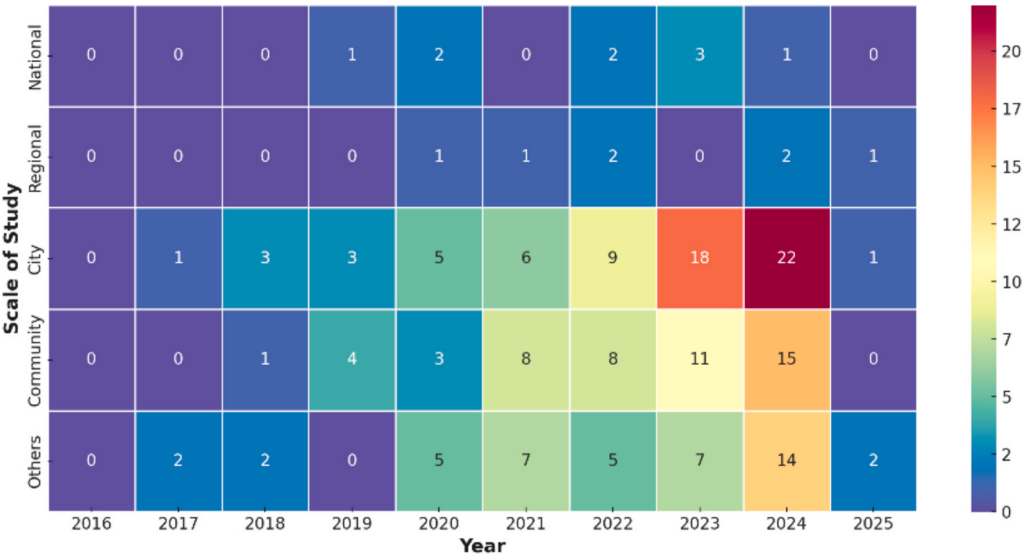


Fig. 3. Annual distribution of UBE studies by scale of analysis.

reflecting the growing role of data-driven methods and algorithmic refinement in UBE practice. Additionally, the appearance of terms such as “urban planning”, “sustainability”, “CO₂ emissions”, and “climate change” at the network’s periphery signals a gradual but

notable shift toward integrative approaches that connect UBE outputs with broader policy agendas. This finding reinforces the relevance of linking UBE to sustainability frameworks like the SDGs. This network illustrates the growing multidisciplinary of UBE research, blending

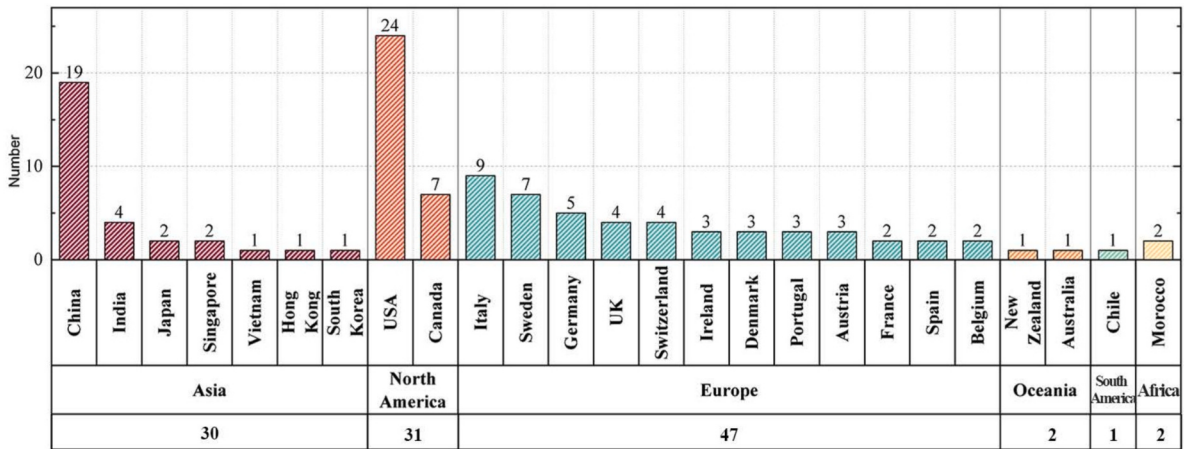


Fig. 4. Geographic distribution of UBE M studies by country and continent.

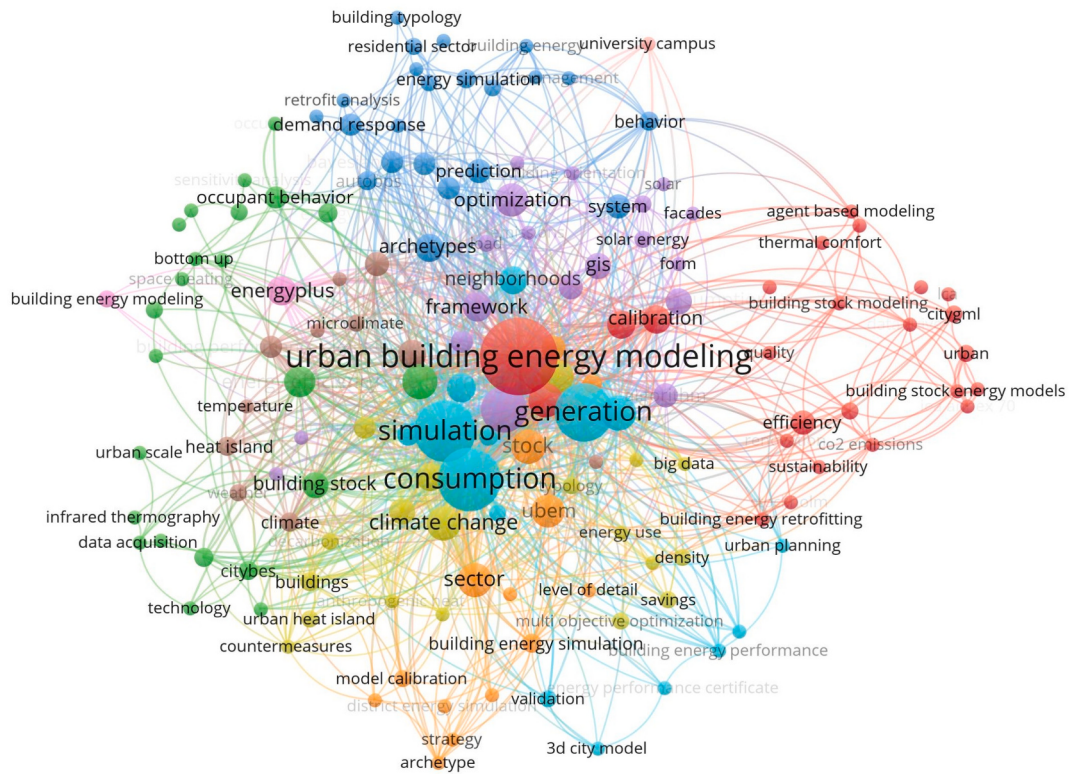


Fig. 5. Keyword co-occurrence network of UBE M literature.

engineering, data science, behavioural analysis, and planning. The clustering patterns reveal both the maturity of core simulation techniques and the expansion into adjacent domains, indicating fertile ground for further cross-sector integration.

The temporal evolution of prominent keywords in UBE M-related literature is shown in Fig. 6, highlighting their burst strength and active periods between 2017 and 2025, as no paper in 2016 is found from literature scanning process. Each keyword reflects a focal topic that has gained academic attention during a particular time span. The earliest keyword bursts began in 2017, including “residential building stock”, “sector”, and “calibration”, indicating early concerns with archetype development and model validation in UBE M’s foundational phase. These themes represent the initial efforts to translate building-level energy simulation practices to urban-scale settings. As the field matured, a second wave of keywords appeared in 2019 and 2020,

including “building energy use”, “climate”, “classification”, and “demand”. These terms suggest a shift toward understanding usage patterns and broader climatic implications, aligning with the integration of UBE M into climate mitigation strategies and more granular demand forecasting. The keyword “demand” notably shows the highest burst strength, reflecting an intensified focus on predicting and managing energy loads at scale. More recent bursts from 2021 onward involve terms such as “algorithm”, “countermeasures”, “residential buildings”, and “building energy simulation”, indicating the rise of computational advancements and growing interest in retrofitting strategies for housing sectors. The emergence of “impacts” and “building energy modeling” in 2022 and 2023, respectively, marks a further evolution toward evaluating broader sustainability outcomes and generalising modelling capabilities. The temporal pattern of these keyword bursts reveals how UBE M research has transitioned from technical model development

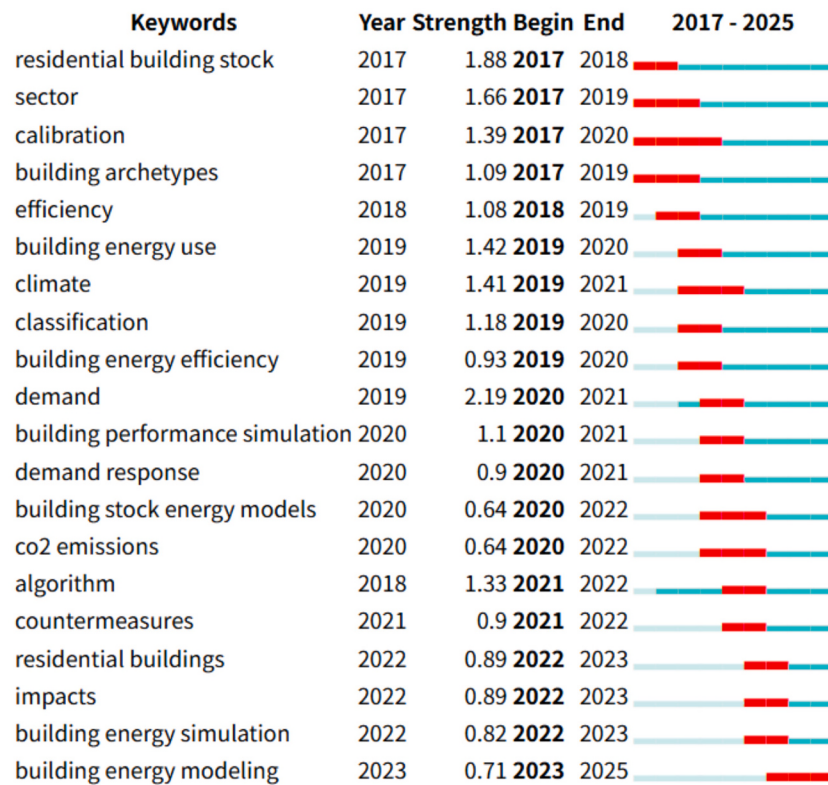


Fig. 6. Temporal trends of top 20 emerging UBEM research keywords.

toward more integrated and impact-oriented themes. This trajectory reflects the field's response to rising policy ambitions, digitalisation trends, and the growing need to evaluate urban energy interventions through a systemic sustainability lens.

These findings in this section demonstrate that while UBEM research has made notable technical advancements, it remains limited by issues of geographical concentration, narrow typological focus, and insufficient contextual diversity. The current emphasis on cities in the Global North, often high-density, temperate, and economically developed urban area, has fostered a body of knowledge that may not adequately reflect the varied challenges and realities of cities in the Global South, particularly those in tropical climates, low-density settlements, or economically constrained contexts. This imbalance not only restricts the applicability and generalisability of UBEM approaches but also raises concerns about epistemic equity and the capacity of current frameworks to support inclusive sustainability transitions. Moreover, the observed growth in publication volume, particularly from 2018 onwards, suggests that UBEM research is increasingly intertwined with broader structural trends, including global climate commitments, the proliferation of smart city policies, and the technological rise of urban digital twins. These external drivers have catalysed advances in data integration and modelling capabilities, yet they also risk reinforcing disparities by privileging digitally mature contexts. Thematic mapping of keywords further illustrates how the field is gradually transitioning from foundational modelling concerns toward impact-oriented and integrative approaches, although sustainability, equity, and socio-political dimensions remain peripheral. To fully realise UBEM's potential as a global tool for supporting the SDGs, future research must actively extend its spatial, disciplinary, and methodological horizons. This includes strengthening engagement with underrepresented geographies, adopting more inclusive frameworks, and embedding UBEM within broader systems-thinking approaches that capture the socio-technical complexity of urban sustainability transitions.

4. UBEM and SDGs from mapping to practical implementation

UBEM is increasingly recognised as a valuable tool for advancing progress toward the SDGs, with the capacity to inform strategies that address interconnected environmental and socio-economic challenges. In this study, its links to the SDGs are examined using SDG labels assigned by Elsevier's Scopus SDG-mapping tool. Fig. 7 presents the distribution of reviewed papers across all goals, with the number above each bar indicating the total count and the percentage showing its share of the dataset. The mapping results show that most studies are closely related to SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), SDG 12 (Responsible Consumption and Production) and SDG 13 (Climate Action), which aligns with the general understanding of the UBEM research focus. Goals with fewer links include SDG 1 (No Poverty), SDG 4 (Quality Education), SDG 8 (Decent Work and Economic Growth), SDG 9 (Industry, Innovation and Infrastructure), SDG 15 (Life on Land) and SDG 17 (Partnerships for the Goals).

The discussion first examines in detail the highly relevant SDGs (7, 11, 12 and 13) and then moves to a concise review of those with more limited relevance, reflecting both the scope and depth of the current evidence base. For any SDG where the reviewed literature identifies more than two distinct UBEM-related functions, a schematic diagram is included. Functions are synthesised from the reviewed studies, while the corresponding targets follow the official SDG framework, where each target specifies a concrete objective within its respective goal. The diagrams illustrate how each function supports its associated targets and how the functions interact, revealing potential synergies and reinforcing effects. This visualisation supplements the statistical mapping and provides a clearer representation of UBEM's practical contributions. The section closes with an exploration of cross-cutting trade-offs and implementation challenges that span multiple SDGs. It considers how to balance higher urban density with adequate ventilation, how to safeguard privacy when handling socio-technical data, and how data

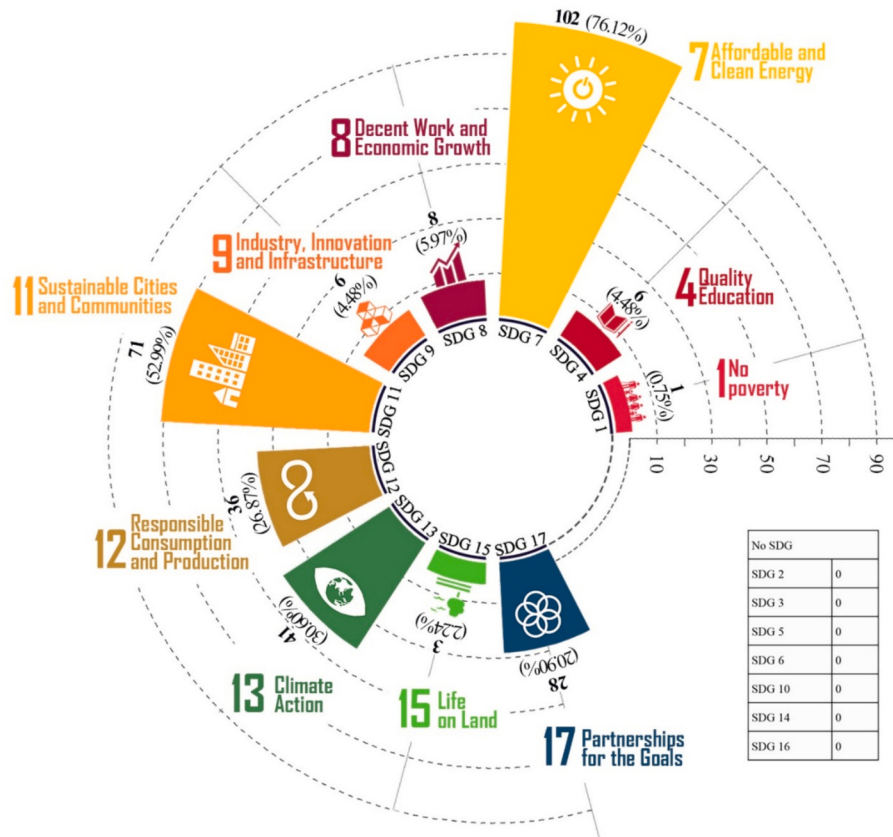


Fig. 7. Statistics of the SDGs covered in the papers reviewed.

quality, interoperability and governance affect the adoption of UBEM in practice. Building on the mapping results, the discussion offers a critical perspective on how UBEM aligns with the broader objectives of sustainable and inclusive urban development.

4.1. SDGs with high relevance to UBEM

UBEM's capabilities are closely aligned with several SDGs that are inherently technical and environmental in nature. These SDGs emphasise energy efficiency, urban resilience, and sustainable consumption, areas where UBEM has demonstrated strong analytical potential. This subsection explores how UBEM supports these high-relevance goals, underlining its role in advancing energy and environmental sustainability.

4.1.1. SDG 7 affordable and clean energy

SDG 7 focuses on ensuring access to affordable, reliable, sustainable, and modern energy. In the urban context, where energy demand is concentrated and infrastructure is complex, achieving this goal requires advanced and integrative approaches. UBEM serves as a transformative tool in this effort, enabling detailed analysis and strategic planning at a city-wide scale. By incorporating diverse data streams, such as building geometry, occupancy patterns, energy systems, and environmental factors, UBEM facilitates a comprehensive understanding of urban energy dynamics, directly aligning with the objectives of SDG 7.

Through its computational framework, UBEM supports the identification of energy inefficiencies, the optimisation of resource allocation, and the integration of clean energy technologies. These capabilities provide the foundation for addressing the core priorities of SDG 7, including enhancing energy accessibility, promoting renewable energy adoption, improving energy efficiency, promoting renewable energy adoption, optimising the grid system and streamlining resource

allocation. By bridging technical energy modelling with the principles of sustainability, UBEM allows urban planners and policymakers to implement targeted interventions that are both efficient and socially inclusive. The relationships between UBEM functionalities and SDG 7 can be visualised as a synergistic system. These functionalities do not operate in isolation but complement and reinforce each other, creating a closed-loop system of feedback and improvement. Fig. 8 illustrates these interconnected capabilities and their contributions to SDG 7 targets. Table 2 reflects how UBEM specifically fulfils each functions.

Building on this foundation, UBEM addresses the dual challenges of urban energy efficiency and social equity through its interrelated functionalities. These include enhancing energy accessibility and self-sufficiency, promoting clean and sustainable energy solutions, improving energy efficiency and management, optimising systems for peak demand and electrification, and streamlining funding and resource allocation. Each function aligns with specific urban needs and technical challenges, while collectively forming a framework to operationalise SDG 7 comprehensively.

Enhancing energy accessibility directly addresses systemic issues of energy poverty and inequity. UBEM achieves this by applying GIS tools and demographic data to identify underserved regions [51,52], simulating decentralised energy systems such as microgrids and distributed storage [53,54], and ensuring equitable access to energy-saving measures [55–58]. These efforts empower vulnerable populations, improve local energy independence, and reduce disparities in energy access. However, gaps remain in explicitly addressing financial and infrastructural barriers for low-income communities, limiting the scalability of equitable energy solutions. Promoting clean and sustainable energy solutions focuses on transitioning from fossil fuels to renewable energy sources. UBEM supports this transition through tools that evaluate solar PV potential [59–64], integrate renewable heating technologies like geothermal heat pumps [56,65–68], and simulate clean energy

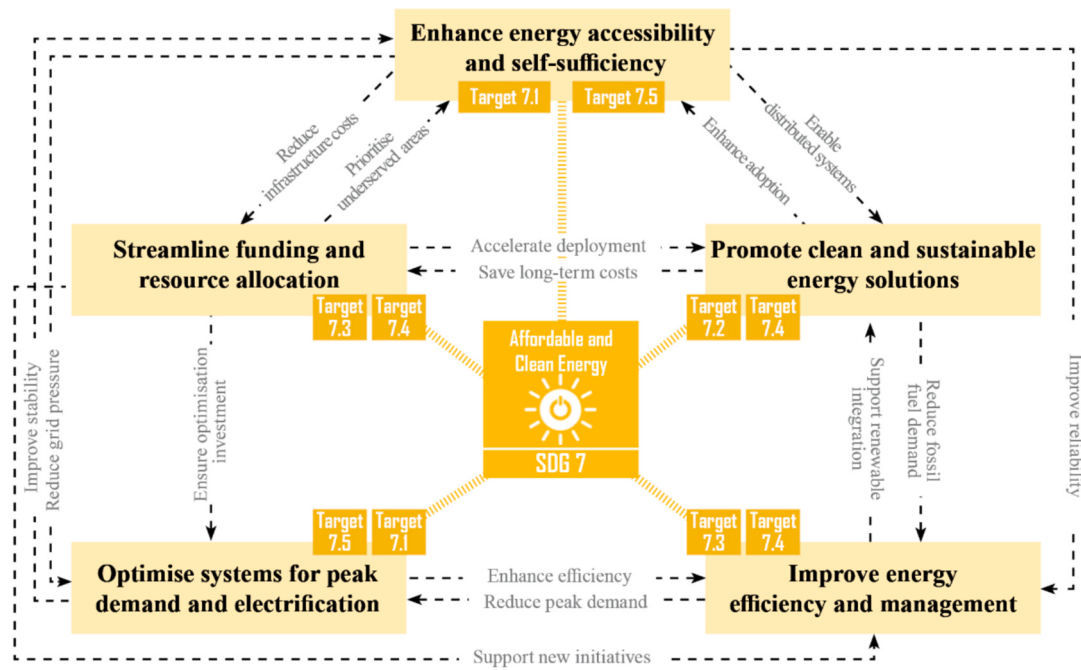


Fig. 8. Framework for linking UBEW with SDG 7.

demonstration projects [69,70]. These efforts reduce emissions and promote sustainable urban energy systems. Yet, challenges such as affordability and public acceptance, particularly for disadvantaged groups, highlight the need for UBEW frameworks to incorporate stronger community engagement strategies. Improving energy efficiency and management reduces the economic burden of energy inefficiency and addresses environmental concerns. UBEW identifies retrofitting opportunities [56,58,66,71,72] and optimises urban designs [73–76], enabling targeted interventions to lower energy consumption and costs. This is especially impactful for older, inefficient building stocks often inhabited by low-income populations. However, the prioritisation of retrofitting measures frequently overlooks socioeconomic factors and lacks participatory decision-making processes, which could otherwise enhance inclusivity. Optimising systems for peak demand and electrification ensures grid stability and facilitates the transition to sustainable heating and cooling systems. UBEW supports demand-response strategies [53,73] and integrates distributed energy systems like district energy networks [52,77–81]. These functionalities reduce dependence on fossil fuels and improve grid resilience. However, affordability and accessibility for low-income households remain inadequately addressed, limiting the broader impact of these solutions. Streamlining funding and resource allocation addresses financial and policy challenges in energy transitions. UBEW provides data-driven insights to prioritise retrofitting projects [66] and design government incentive programmes [57,72]. By aligning funding strategies with social priorities, such as reducing energy costs for disadvantaged populations, UBEW ensures that resources are used effectively. Nonetheless, funding mechanisms often fail to explicitly target the financial barriers faced by low-income households, underscoring the need for greater equity in policy design.

These functionalities form a closed-loop system of mutual support, ensuring that SDG 7 objectives are achieved holistically and sustainably. Clean and sustainable energy serves as the central direction for future energy transitions, with energy efficiency and management acting as critical enablers to realise this goal. Accessibility and self-sufficiency address the social equity dimensions of energy supply and demand, ensuring underserved populations benefit equitably. System optimisation provides the technical foundation for implementing these solutions effectively, while funding and resource allocation ensure the long-term feasibility and scalability of the strategies.

This synergistic relationship among UBEW functionalities drives sustainable energy supply, optimised energy efficiency, and equitable energy access, enabling the comprehensive realisation of SDG 7. By addressing technical gaps and aligning advancements with broader urban planning objectives, UBEW ensures that urban energy transitions are efficient, sustainable, and seamlessly integrated into the overall urban ecosystem.

4.1.2. SDG 11 sustainable cities and communities

UBEW plays a crucial role in achieving the objectives of SDG 11, which aims to make cities inclusive, safe, resilient, and sustainable. UBEW's ability to provide detailed insights into urban energy systems enables more equitable, efficient, and community-focused urban planning. The alignment of UBEW with SDG 11 addresses various targets, including promoting sustainable urban planning, supporting urban building retrofitting, integrating renewable energy systems, advancing UBEW data accuracy, and enhancing urban energy efficiency. Fig. 9 depicts the interrelated capabilities and their roles in achieving the targets of SDG 11. Table 3 illustrates the specific functions fulfilled by UBEW.

One critical application of UBEW in advancing SDG 11 is the enhancement of urban planning tools. UBEW offers data-driven insights that allow planners to enhance energy efficiency and integrate renewable strategies into urban frameworks. By simulating various energy demand scenarios, UBEW facilitates equitable energy access and identifies opportunities for infrastructure development centred on community needs [51,82–85]. Moreover, UBEW can inform urban planning through climate-adaptive strategies that prioritise climate resilience and the reduction of disaster risk. A consequential aspect of UBEW's relevance is its focus on sustainable building design and retrofitting. UBEW's capacity to analyse building performance data can guide retrofitting strategies, ensuring that existing structures comply with contemporary energy standards while reducing environmental impacts. This supports the objective of facilitating retrofitting via energy-efficient technologies, decreasing energy demand, and enhancing the sustainability of urban infrastructure [56]. Furthermore, precise UBEW modelling enhances equity by revealing disparities in building energy performance among socio-economic groups, facilitating targeted interventions to mitigate energy poverty [56,66,86–89]. Insights from UBEW could substantially

Table 2
Key Functions of UBEM in Supporting SDG 7.

Number	SDG Targets	Functions	How UBEM Supports SDG 7
1	Target 7.1 & Target 7.5	Enhance Energy Accessibility and Self-Sufficiency	• Identify and map energy-poor areas using UBEM spatial outputs • Assess potential for distributed generation and storage to reduce grid dependence • Support equitable energy access planning for underserved communities • Quantify renewable potential for buildings and districts • Model integration of solar PV, renewable heating, and storage
2	Target 7.2 & Target 7.4	Promote Clean and Sustainable Energy Solutions	• Test feasibility of clean energy demonstration projects • Provide scenario-based insights for renewable adoption in policy planning • Evaluate district-level energy sharing models • Detect priority retrofit opportunities using baseline simulations
3	Target 7.3 & Target 7.4	Improve Energy Efficiency and Management	• Analyse urban form changes for their impact on energy demand • Support flexible demand and load shifting strategies • Provide evidence for operational optimisation of building clusters • Simulate district-scale demand response strategies
4	Target 7.1 & Target 7.5	Optimise Systems for Peak Demand and Electrification	• Evaluate electrification pathways for heating and cooling • Assess hybrid central-distributed supply configurations • Rank retrofit measures by cost-effectiveness and carbon savings
5	Target 7.3 & Target 7.4	Streamline Funding and Resource Allocation	• Use spatial mapping to target public funding • Identify private investment opportunities through scenario modelling • Support development of regulatory and incentive frameworks

enhance climate adaptation and the integration of renewable energy. UBEM models evaluate the resilience of urban systems across various climate scenarios, facilitating the enhancement of energy resilience via renewable systems and climate-adaptive solutions. Incorporating these insights into urban planning frameworks enables cities to endure and recuperate from climate-related disruptions while ensuring equitable access to energy resources [85,90]. UBEM enhances urban energy efficiency and demand reduction initiatives through the facilitation of detailed energy data analysis and the promotion of efficient building design. This approach reduces energy demand and facilitates the integration of renewable energy systems into urban grids, thereby contributing to the decarbonisation of urban areas [83,91–93]. UBEM significantly contributes to sustainable community development by providing actionable insights that inform policy-making [94–96], emphasising energy equity and resilience [97].

Overall, UBEM provides a reliable and robust platform for aligning urban energy systems with the targets of SDG 11. Its capacity to synthesise data from diverse sources, predict future scenarios, and guide

policy interventions ensures that cities can progress toward greater inclusivity, resilience, and sustainability. Its broader viewpoint underscores UBEM's potential for shaping strategies that prioritise urban well-being in tandem with energy efficiency.

4.1.3. SDG 12 responsible consumption and production

SDG 12 focuses on promoting sustainable consumption and production patterns by improving resource efficiency, reducing waste, and encouraging responsible practices. UBEM actively supports these objectives through enhancing resource efficiency, enabling sustainable consumption and production, advancing energy performance and addressing policy and decision-making challenges. Fig. 10 illustrates the synergy among various capabilities in supporting SDG 12 targets, with Table 4 providing an overview of UBEM's specific roles.

UBEM strengthens resource efficiency by analysing energy use across urban and industrial systems, identifying areas of inefficiency, and enabling targeted improvements [56,66,98–103]. These strategies reduce energy waste, optimise resource use, and drive the adoption of more sustainable production methods. However, many current applications of UBEM focus on technical outputs and overlook how these interventions could be made accessible to underserved populations, limiting their broader impact. By advancing energy performance, UBEM uses data insights to optimise energy systems and inform sustainability strategies [54,60,78,88,104–107]. It provides actionable recommendations that align production and consumption patterns with environmental goals, ensuring urban systems operate efficiently. Despite this, existing UBEM implementations often favour large-scale solutions, leaving the unique energy needs of smaller communities or decentralised systems underexplored. UBEM also aligns decisions with sustainable production and consumption targets by providing evidence-based insights into resource-saving behaviours and practices [7,60,69,108,109]. These insights help policymakers and industries design strategies to reduce resource-intensive activities and encourage responsible practices. However, many of these strategies lack the flexibility to involve marginalised groups in the decision-making process or to adapt solutions to the needs of resource-constrained regions. Finally, UBEM addresses policy and decision-making challenges by offering standardised frameworks and actionable data that guide the development of effective sustainability strategies [58,62,105,110]. By integrating energy performance evaluations into policymaking, UBEM ensures that energy solutions are both actionable and relevant to the broader targets of SDG 12. Nonetheless, these frameworks often fail to address the distribution of benefits, leaving questions about equity and accessibility unaddressed.

Together, these functions form an integrated framework for supporting SDG 12 by improving resource efficiency, optimising energy systems, aligning decisions with sustainable practices, and enhancing policymaking. To fully address SDG 12, however, UBEM must prioritise inclusivity by tailoring its tools and strategies to meet the needs of disadvantaged populations. Addressing these gaps ensures that UBEM not only contributes to sustainability but also advances equitable and inclusive development.

4.1.4. SDG 13 climate action

SDG 13 focuses on urgent actions to combat climate change and its impacts, emphasising the transition to low-carbon systems and sustainable energy practices. UBEM contributes to this goal by supporting low-carbon development, enabling climate-resilient urban systems, and promoting sustainable energy strategies. Fig. 11 provides a visual representation of the interconnected capabilities and specific contributions of UBEM aiding SDG 13.

UBEM supports low-carbon and climate-friendly development by providing data-driven tools to quantify and reduce carbon emissions [76,111–114]. By modelling carbon reductions through retrofits and renewable energy integration, UBEM identifies high-impact areas for decarbonisation at both the building and district levels. These models

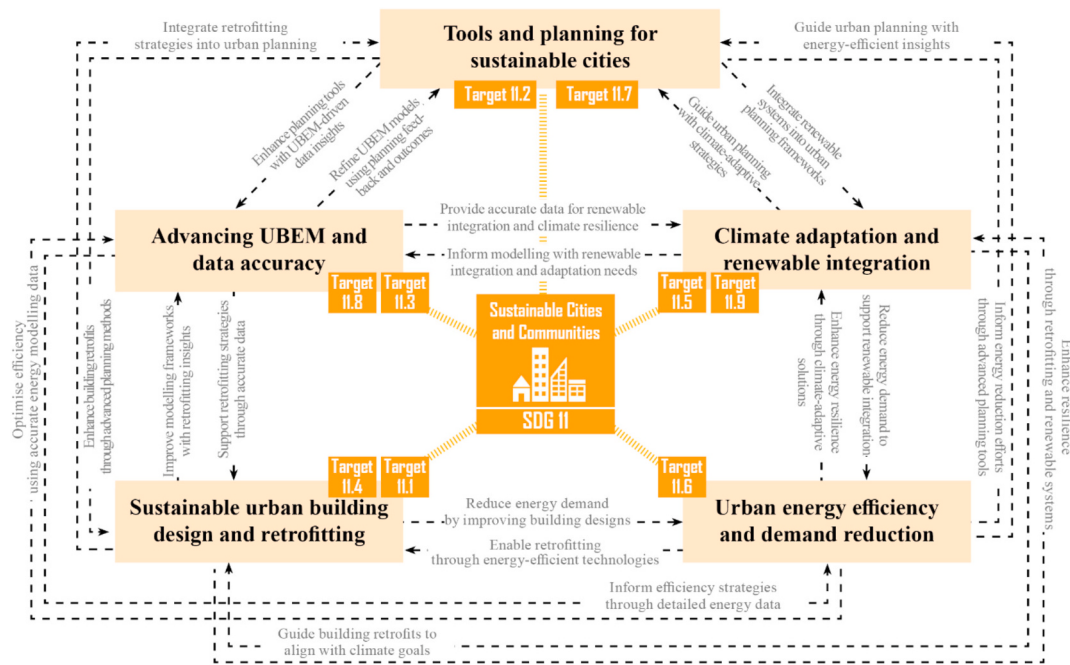


Fig. 9. Framework for linking UBEW with SDG 11.

assist in formulating decarbonisation pathways, such as integrating photovoltaic systems and district heating solutions, and evaluating their effectiveness under various climate and retrofit scenarios. Moreover, UBEW equips policymakers with actionable insights, helping to shape policies that align with climate targets and ensure orientated, impactful interventions. In addition to low-carbon transitions, UBEW advances sustainable energy practices by enhancing renewable energy adoption and adapting urban energy systems to future climate conditions [6,115–121]. It facilitates the integration of renewable technologies to reduce reliance on fossil fuels and improves the adaptability of urban systems to climate-related risks, such as extreme weather events. Furthermore, UBEW fosters collaboration among stakeholders, including local governments, planners, and private sector actors, ensuring that sustainable energy strategies are implemented effectively and equitably.

These capabilities come together in a cohesive framework to support SDG 13. By quantifying emissions, proposing decarbonisation strategies, integrating renewable energy, and driving stakeholder collaboration, UBEW addresses the multifaceted challenges of climate action. Its tools and methodologies align low-carbon transitions with sustainable energy adoption, creating a unified approach that enables cities to mitigate emissions, enhance resilience, and support the global fight against climate change.

4.2. SDGs with limited relevance to UBEW

While UBEW primarily focuses on technical and environmental dimensions, its potential contributions to broader societal objectives remain underexplored. Several SDGs, which centre on social equity, education, and poverty alleviation, exhibit limited integration within the current UBEW framework. This subsection examines the intersections of UBEW with these less-studied goals, identifying opportunities for expanding its scope to address societal challenges.

4.2.1. SDG 1 no poverty

SDG 1 seeks to eradicate poverty in all its forms, including addressing inadequate access to secure and affordable housing, which disproportionately affects low-income and marginalised groups. UBEW supports this goal by enabling targeted, economically viable interventions to

improve housing quality and reduce energy-related financial burdens. The details of how UBEW could support could be found in Table B1 in Appendix B.

By employing simulations, UBEW identifies buildings with poor energy performance, enabling retrofits such as improved insulation, upgraded heating systems, and energy-efficient technologies, which directly lower energy expenses, enhance thermal comfort, and alleviate financial burdens on disadvantaged households [111]. By prioritising retrofits in areas with high concentrations of vulnerable populations and strategically directing resources to high-impact projects, UBEW ensures that energy poverty is addressed where it is most critical. Yet, gaps remain in integrating social equity considerations into retrofit prioritisation frameworks, such as accounting for intersecting vulnerabilities like age, disability, or lack of access to financial support. In doing so, UBEW not only promotes equitable access to affordable energy but also contributes to broader efforts to alleviate poverty and foster sustainable, inclusive urban environments. Addressing these gaps would further strengthen UBEW's capacity to align with SDG 1 by creating solutions that are not only efficient and cost-effective but also inclusive and socially equitable.

4.2.2. SDG 4 quality education

SDG 4 focuses on ensuring inclusive and equitable quality education and promoting lifelong learning opportunities for all. This goal highlights the importance of integrating sustainability and practical skills into educational frameworks. UBEW supports this objective by promoting energy education and fostering the engagement of educational institutions in urban energy planning and research. Connections can be found in Fig. 12. Table B1 in Appendix B further clarifies UBEW's supportive roles for SDG 4.

In detail, UBEW promotes energy education by integrating its research into academic programmes and training initiatives. By offering educational content and tools tailored to various skill levels, UBEW seeks to equip learners with the knowledge and skills necessary to advance sustainable development. Accessible UBEW tools, such as open-source modelling platforms, serve as valuable resources for educators and students, facilitating hands-on learning and raising awareness of sustainable energy solutions [115,122]. However, existing UBEW research often lacks frameworks for adapting these tools to diverse educational

Table 3
Key Functions of UBEM in Supporting SDG 11.

Number	SDG Targets	Functions	How UBEM Supports SDG 11
1	Target 11.2 & Target 11.7	Tools and Planning for Sustainable Cities	• Build city-scale UBEM models for integrated planning • Apply simulation-based optimisation for land use and energy systems • Evaluate and minimise spatial errors in model parameter transfer • Test and refine energy-saving strategies at the community scale
2	Target 11.1 & Target 11.4	Sustainable Urban Building Design and Retrofitting	• Assess and optimise building envelopes for climate performance • Analyse building energy networks for efficiency gains • Provide evidence-based plans for low-energy neighbourhoods • Quantify renewable generation potential in urban districts
3	Target 11.5 & Target 11.9	Climate Adaption and Renewable Integration	• Integrate real-time weather data to simulate adaptation strategies • Model effects of ventilation corridors and vegetation on cooling • Explore synergies between passive design and renewable supply • Develop scalable modelling frameworks for different urban contexts
4	Target 11.3 & Target 11.8	Advancing UBEM and Data Accuracy	• Incorporate satellite and aerial thermal imagery to refine inputs • Link UBEM with spatial planning tools for integrated decision-making • Identify priority retrofit projects with high impact potential
5	Target 11.6	Urban Energy Efficiency and Demand Reduction	• Simulate demand reduction scenarios for peak load management • Estimate resource savings to support policy funding decisions

contexts, limiting their reach to specialised academic audiences. Furthermore, UBEM fosters the engagement of educational institutions by developing workflows that enable their active participation in urban energy planning [116]. This includes using campuses as living laboratories for UBEM research, where real-world data informs modelling techniques and practical applications. By incorporating UBEM into institutional workflows, universities and schools can play a proactive role in advancing sustainable energy transitions while simultaneously improving the quality of education. Nonetheless, challenges persist in scaling these collaborations and ensuring that smaller institutions or those in under-resourced areas have the capacity to participate effectively.

Through these two primary functions, namely promoting energy education and engaging educational institutions, UBEM not only enhances access to quality education but also bridges the gap between theoretical learning and practical sustainability initiatives. However, to fully align with SDG 4, existing UBEM practices must address gaps in accessibility and inclusivity, ensuring that educational tools and opportunities are equitable and scalable across diverse contexts. By doing

so, UBEM can play a transformative role in advancing SDG 4 while contributing to sustainable urban development.

4.2.3. SDG 8 decent work and economic growth

SDG 8 focuses on promoting sustained, inclusive, and sustainable economic growth, full and productive employment, and decent work for all. UBEM can contribute to achieving this goal by addressing the interconnected objectives of economic stability, job creation, and energy system resilience. The interconnected contributions of UBEM to SDG 8 are illustrated in Fig. 13. This diagram highlights how UBEM aligns with the targets of economic sustainability, cost and risk management, job creation, and growth resilience. Refer to Table B1 in Appendix B for a breakdown of how UBEM could provide support SDG 8.

UBEM offers a detailed analysis of urban energy consumption, facilitating data-informed decision-making for policymakers and stakeholders regarding building energy retrofits and efficiency enhancements. The decisions enhance the economic sustainability of urban development by lowering energy expenses and stabilising markets. Policymakers can utilise these insights to create regulatory frameworks that encourage investments in energy efficiency and safeguard vulnerable populations from economic instability [123]. Models driven by UBEM can identify cost-effective energy-saving measures, ensuring that retrofitting projects adhere to budget constraints while maximising impact. Through the simulation of energy performance scenarios, UBEM enables the formulation of targeted subsidy programs, thereby optimising resource allocation to maximise both economic and environmental benefits [54,56,124]. Retrofitting to improve building insulation and incorporate renewable energy sources reduces operational costs and enhances property values, resulting in wider economic advantages. UBEM's capacity to model urban energy systems at scale allows stakeholders to identify and mitigate risks related to energy investments. Utilising high-resolution data and simulation capabilities, UBEM assesses the financial viability of retrofitting projects and energy upgrades [56,68,93,123,124]. This analysis demonstrates the potential for establishing stable energy markets through the reduction of uncertainties and the improvement of investor confidence. The implementation of UBEM-informed retrofitting and energy upgrade projects could create employment opportunities. As urban areas aim to achieve energy efficiency objectives, there is a growing demand for skilled labour in construction, engineering, and energy modelling [54,56,122]. UBEM enhances the resilience of urban energy systems through the identification of strategies aimed at decreasing dependence on fossil fuels and improving energy efficiency. These strategies mitigate environmental risks while enhancing the economic resilience of urban areas. Resilient energy systems facilitate sustained economic growth by providing a stable energy supply for both businesses and households [56,92,93].

By providing actionable insights and fostering collaboration among stakeholders, UBEM serves as a critical enabler of sustainable urban development. UBEM's multifaceted capabilities address the core objectives of SDG 8 by enhancing economic sustainability, stabilising markets, driving employment, and fostering resilience. By integrating these functions into urban energy planning, UBEM not only supports economic growth but also ensures that it is inclusive and sustainable. The closed-loop and collaborative nature of these functionalities ensures that progress in one area directly supports advancements in others, creating a robust and resilient framework for achieving SDG 8.

4.2.4. SDG 9 industry, innovation and infrastructure

SDG 9 focuses on building resilient infrastructure, fostering innovation, and promoting sustainable industrialisation to support inclusive and sustainable development. UBEM plays a crucial role in achieving this goal by improving energy efficiency, advancing energy infrastructure, and creating adaptable frameworks to enable innovation and scalability in urban energy systems. The interconnected contributions of UBEM to SDG 9 are illustrated in Fig. 14. Insights into how UBEM

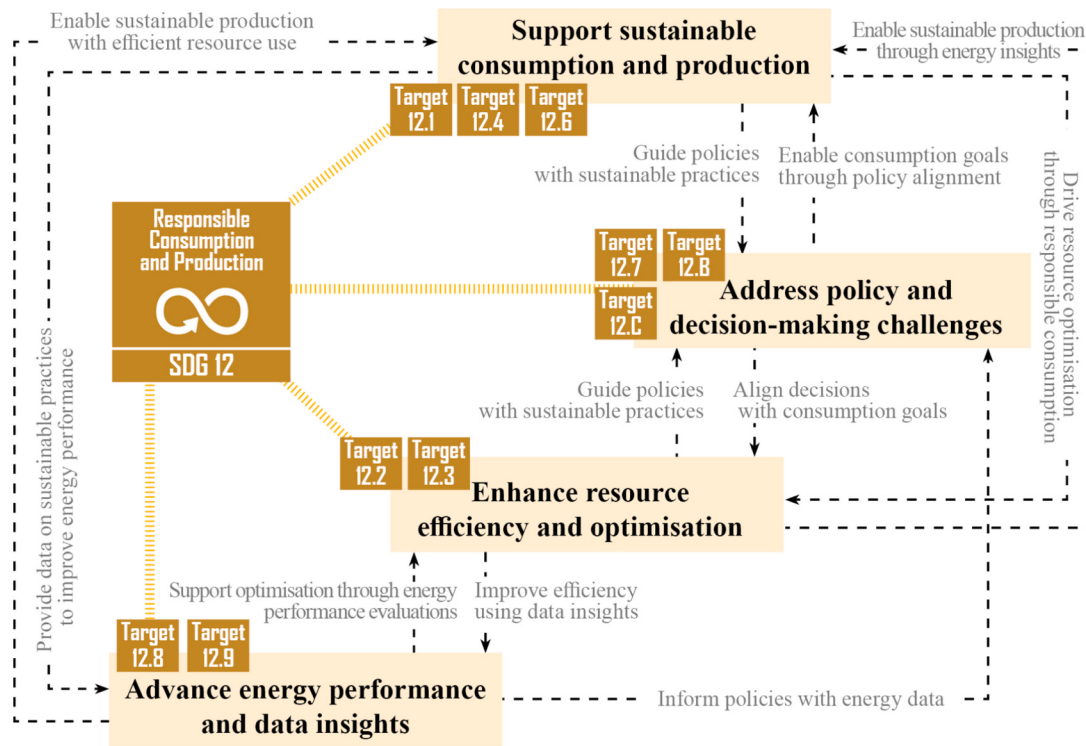


Fig. 10. Framework for linking UBE M with SDG 12.

support SDG 9 are outlined in Table B1 in Appendix B.

UBEM contributes to innovation and infrastructure improvement by using advanced modelling to optimise energy systems and identify inefficiencies [86]. These insights enable targeted upgrades that reduce environmental impact while modernising urban and industrial systems. However, many UBE M applications prioritise efficiency and scalability, often overlooking how infrastructure upgrades could better support underrepresented or resource-constrained communities. UBE M could also advance sustainable energy infrastructure by integrating data-driven technologies [86,125,126]. These tools support adaptive and efficient systems across diverse contexts, ensuring long-term sustainability. While UBE M promotes renewable energy adoption and integrated energy solutions, existing studies often lack frameworks to prioritise underserved regions or ensure affordability, leaving equity considerations underexplored. In addition, UBE M develops scalable frameworks that standardise data integration and improve modelling efficiency, allowing solutions to be deployed across varied settings [84,98,125]. However, these frameworks frequently focus on large-scale applications, limiting their relevance to smaller-scale industries or marginalised areas.

By enhancing energy performance, supporting resilient infrastructure, and fostering innovative frameworks, UBE M makes contributions to SDG 9. In order to fully address this goal, UBE M studies should bridge equity gaps by prioritising inclusivity, improving access for underserved communities, and tailoring solutions to diverse needs. Such efforts will ensure that UBE M drives not only sustainable but also inclusive industrial and infrastructure development.

4.2.5. SDG 15 life on land

SDG 15 focuses on protecting, restoring, and promoting the sustainable use of terrestrial ecosystems, sustainably managing forests, combating desertification, halting and reversing land degradation, and curbing biodiversity loss. UBE M can support this goal by providing sustainable and efficient solutions to mitigate the environmental impacts of urban energy systems. Additional details about UBE M's support capabilities to SDG 15 are in Table B1 in Appendix B.

Specifically, UBE M reduces greenhouse gas emissions and energy demand by simulating low-carbon heating systems [81]. By modelling the integration of renewable energy technologies, such as geothermal and solar systems, UBE M facilitates the transition to cleaner energy systems, aligning with the targets of reducing urban emissions and minimising their impacts on land and biodiversity. At the same time, UBE M helps to minimise environmental impacts by assessing urban energy-saving strategies [127,128]. It identifies opportunities to improve energy efficiency while reducing resource consumption, ensuring that urban energy planning supports sustainable land use and ecosystem preservation. Additionally, UBE M informs urban block designs that balance building density with green spaces. By combining energy modelling with urban design, UBE M enables planners to create layouts that lower energy intensity while protecting natural ecosystems, contributing to biodiversity conservation and land restoration targets.

Through these functions, UBE M supports SDG 15 by reducing environmental pressures associated with urbanisation and promoting sustainable land management. However, incorporating biodiversity metrics and local land-use considerations more comprehensively into UBE M frameworks could further enhance its contribution, ensuring urban systems coexist harmoniously with natural ecosystems.

4.2.6. SDG 17 partnerships for the goals

SDG 17 emphasises the importance of fostering collaboration and building partnerships to drive sustainable development. Achieving this objective requires coordinated efforts among diverse stakeholders, open access to data and resources, and the development of scalable frameworks that can address the unique challenges of urban energy systems. UBE M contributes to SDG 17 by enabling multi-stakeholder collaboration, creating adaptable frameworks, and promoting the sharing of knowledge to support global energy transitions. The connections between UBE M and SDG 17 are shown in Fig. 15, and more details about how UBE M support this SDG, as shown in Table B1.

UBEM supports partnerships by utilising shared data and encouraging collaboration among local communities, policymakers, researchers, and private organisations [55,56,62,104,128]. By providing

Table 4
Key Functions of UBEM in Supporting SDG 12.

Number	SDG Targets	Functions	How UBEM Supports SDG 12
1	Target 12.2 & Target 12.3	Enhance Resource Efficiency and Optimisation	- Integrate building-integrated photovoltaics into energy models - Apply detailed UBEM frameworks to optimise retrofit planning - Use aerial thermal imagery to detect inefficiencies - Quantify material use and savings in retrofit measures - Evaluate alternative building configurations for energy efficiency
2	Target 12.1 & Target 12.4 & Target 12.6	Support Sustainable Consumption and Production	- Optimise energy distribution within urban networks - Design and assess hybrid renewable energy systems - Provide data-driven insights to improve energy performance
3	Target 12.7 & Target 12.8 & Target 12.C	Advance Energy Performance and Data Insights	- Reduce waste through predictive and lifecycle analysis - Apply monitoring results to refine operational strategies - Support evidence-based sustainable development policies
4	Target 12.8 & Target 12.9	Address Policy and Decision-making Challenges	- Standardise modelling practices for decision support - Identify and address policy gaps affecting resource efficiency

platforms for collective input, UBEM ensures diverse perspectives are integrated into urban energy planning. This approach strengthens decision-making processes and fosters alignment between stakeholders

to deliver effective and inclusive energy solutions. However, greater efforts are required to ensure equitable participation from underrepresented regions and resource-constrained organisations, which must be addressed to enhance inclusivity and maximise impact. In addition, UBEM drives the development of scalable and adaptable frameworks tailored to varied urban contexts and climatic conditions [59,87]. By incorporating global climate models and archetype-based methods, UBEM ensures that its solutions are contextually relevant and applicable across diverse geographies. GIS-based tools further enable coordination between the public and private sectors, enhancing urban energy planning processes. These efforts focus on using technology and fostering international cooperation to achieve sustainable development targets. UBEM also advances global knowledge exchange by publishing open-access tools and reproducible frameworks [93]. These efforts encourage cross-disciplinary collaboration and transparency, enabling the wider adoption of energy optimisation strategies. Standardisation and the integration of machine learning methodologies further enhance the scalability and accuracy of UBEM applications, facilitating the implementation of sustainable urban energy solutions globally.

Together, these functions form a cohesive framework that addresses the multidimensional requirements of SDG 17. By combining stakeholder collaboration, scalable framework development, and knowledge dissemination, UBEM supports the creation of strong, inclusive partnerships for the global transition to sustainable energy systems. This

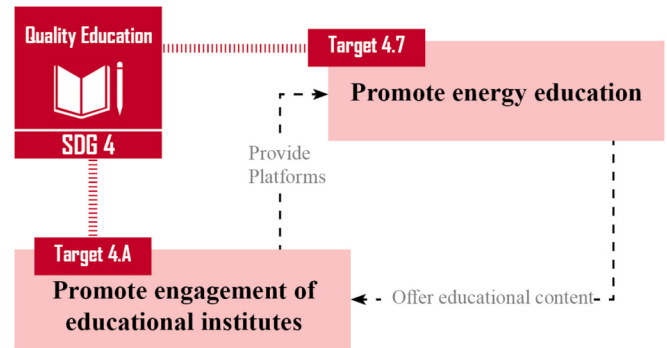


Fig. 12. Framework for linking UBEM with SDG 4.

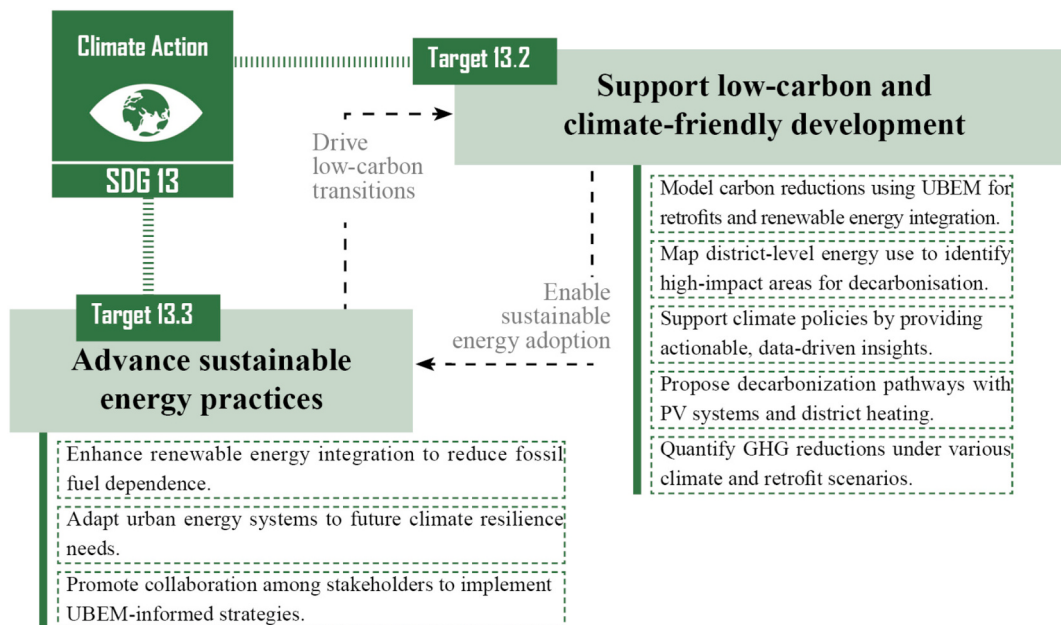


Fig. 11. Framework for linking UBEM with SDG 13.

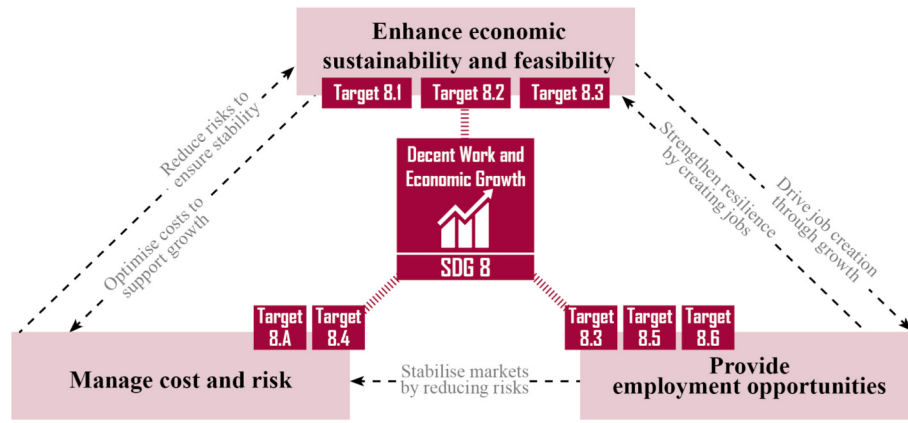


Fig. 13. Framework for linking UBE with SDG 8.

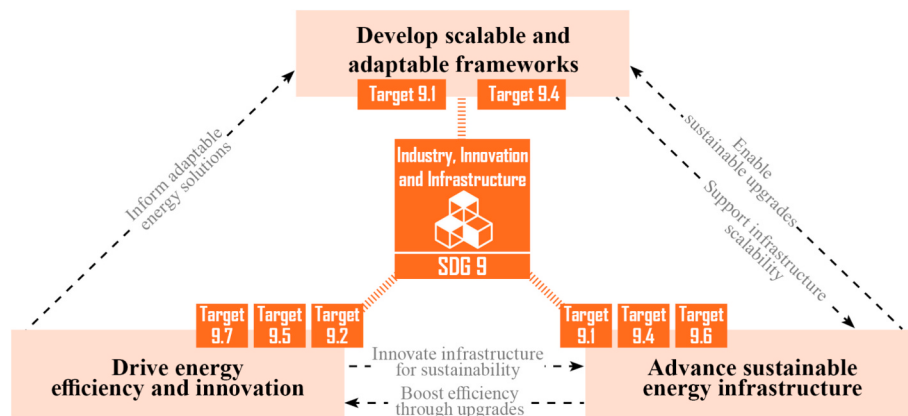


Fig. 14. Framework for linking UBE with SDG 9.

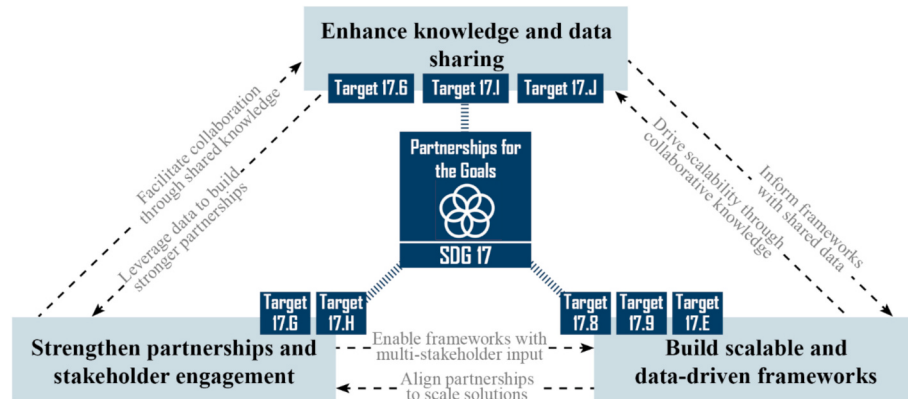


Fig. 15. Framework for linking UBE with SDG 17.

integrated approach ensures that technological innovation, collective expertise, and shared resources are harnessed to deliver impactful solutions, enabling UBE to play a transformative role in advancing SDG 17 and fostering sustainable urban development worldwide.

4.3. Cross-cutting trade-offs and implementation challenges

UBE can support a wide range of SDG targets, yet the translation of modelling outputs into practical urban strategies often involves balancing competing priorities. Increasing urban density, for example, may improve land-use efficiency and reduce transport emissions, but

can also limit natural ventilation and increase heat stress in warm climates [129]. Using detailed socio-technical data can help to identify underserved communities and target interventions, but may raise privacy concerns and affect public trust [26]. Energy retrofits can deliver substantial efficiency gains and improve comfort, yet their costs can place additional burdens on lower-income households [130]. Such cases highlight the need to assess the broader social and environmental implications of UBE-informed policies alongside their technical performance.

Delivering these applications at scale requires overcoming persistent barriers. From a technical perspective, reliable outputs depend on

effective calibration at the urban scale [24], supported by consistent and high-quality data on building stocks, occupancy, and energy systems. Limited interoperability between UBEM platforms and other urban modelling tools can restrict integration with planning processes [18], while high computational requirements may limit use in settings with fewer resources. Governance arrangements also shape outcomes, as responsibilities are often spread across different agencies, utilities, and private actors, making coordination more complex. Building trust in model results relies not only on transparent methods but also on developing the skills needed to interpret and apply them effectively.

Addressing these challenges benefits from involving policymakers, practitioners, and communities in the design and application of UBEM studies. Collaborative approaches can help to reconcile conflicting objectives, identify acceptable compromises, and ensure that modelling outputs remain relevant to real-world decisions. Embedding UBEM in established policy processes and maintaining feedback between implementation and modelling can strengthen both its influence and its credibility, supporting progress toward SDG targets without undermining other aspects of sustainable urban development.

5. Discussion

This section explores UBEM's contributions to the SDGs, its current limitations, and opportunities for expansion, focusing on enhancing its impact across diverse sustainability challenges.

5.1. Interactions between SDGs in the UBEM context

Although UBEM has typically addressed SDGs individually, many of these goals are deeply interrelated. In practical applications, interventions assessed through UBEM frequently generate effects that span multiple targets. For instance, improving building energy efficiency directly contributes to SDG 7, while simultaneously supporting SDG 3 (Good Health and Well-being) by enhancing indoor environmental conditions and SDG 13 by lowering greenhouse gas emissions. When retrofitting initiatives generate local employment and training opportunities, they also advance SDG 8 and, when directed toward underserved populations, SDG 1 and SDG 10 (Reduced Inequalities).

The integration of renewable energy systems into building stocks contributes to SDG 9 through distributed energy deployment and reinforces SDG 11 by enhancing resilience and decentralisation. If paired with circular design and reduced material demand, such strategies may also support SDG 12. Nonetheless, these synergies are rarely formalised within current modelling structures.

At the same time, potential tensions exist. Enhancing thermal insulation may reduce operational energy use but lead to increased embodied carbon and construction waste, raising challenges for SDG 15. If retrofitting prioritises dense urban cores due to data availability or cost-efficiency, marginalised or peri-urban areas may be neglected, undermining SDG 1 and SDG 10. Moreover, building interventions that proceed without transparency or community involvement may compromise SDG 16 (Peace, Justice and Strong Institutions), particularly where public trust in infrastructure planning is low.

Further gaps emerge in relation to SDG 5 (Gender Equality), as few UBEM applications address gender-differentiated patterns in energy access or thermal vulnerability. In contexts where building-integrated agriculture is promoted, there may be opportunities to connect UBEM scenarios to SDG 2 (Zero Hunger) through co-benefits for rooftop farming and food system localisation. Building energy use also intersects with SDG 6 (Clean Water and Sanitation), particularly where energy-intensive treatment or pumping infrastructure is embedded in the built environment. Finally, cross-jurisdictional collaboration around open UBEM platforms and shared datasets can help advance SDG 17.

5.2. Underexplored aspects of UBEM studies

UBEM has become an indispensable tool for addressing urban energy challenges, providing robust methodologies for understanding and optimising energy consumption in urban areas. Its technical capabilities have demonstrated alignment with SDGs 7, 11, 12, and 13 by enabling detailed simulations of energy systems, assessing retrofit potential, and supporting the integration of renewable energy technologies. These achievements underline UBEM's relevance in promoting clean energy, sustainable urban development, responsible resource use, and climate action. However, as this work highlights, the field remains constrained by geographic imbalances, methodological inconsistencies, and an underdeveloped focus on social equity and collaboration, which limits its ability to address SDGs holistically. While UBEM excels in its contributions to environmental sustainability, its broader impact across other interconnected SDGs, such as SDG 1, SDG 9, SDG 10, and SDG 17, remains insufficiently realised.

5.2.1. Narrow engagement with non-technical dimensions

One of the most pressing limitations of UBEM research lies in its narrow engagement with non-technical dimensions, particularly those central to SDG 1 and SDG 10. While UBEM platforms have achieved technical excellence in optimising energy use and reducing emissions, they have yet to adequately address the socio-economic implications of these interventions. For example, current frameworks rarely account for how energy-saving measures interact with issues such as energy poverty, housing affordability, and equitable access to energy-efficient technologies. This omission is particularly concerning in regions where socio-economic vulnerabilities are acute, such as parts of Africa and South Asia. Without systematic frameworks to evaluate the distributional impacts of energy interventions, UBEM risks reinforcing existing inequalities rather than mitigating them. This disconnect reveals a broader structural limitation within the field: a predominant focus on quantitative outputs at the expense of qualitative assessments that evaluate equity, inclusivity, and justice in urban energy systems.

5.2.2. Application imbalances geographically

The geographic concentration of UBEM research further exacerbates its limited impact on global sustainability. Most studies and applications are concentrated in North America, Europe, and East Asia, reflecting the availability of advanced research infrastructure, policy support, and high-quality data in these regions. Conversely, regions such as Africa, South Asia, and Latin America are underrepresented, despite facing severe energy challenges. These areas often grapple with inadequate infrastructure, limited access to reliable data, and high levels of energy poverty, which current UBEM methodologies are poorly equipped to address. This imbalance not only limits the global applicability of UBEM but also highlights its failure to contribute equitably to SDG 9, which emphasises fostering resilient infrastructure and sustainable industrialisation. To expand its relevance, UBEM research must prioritise capacity-building and data generation in underrepresented regions, fostering collaborative efforts that ensure no region is left behind in the transition toward sustainable urban energy systems.

5.2.3. Methodological inconsistencies and scalability limit

A synthesis across SDG clusters reveals several methodological patterns that recur throughout the UBEM literature, despite the distinct policy orientations associated with each goal. Studies under SDGs 7 and 13 systematically employ high-resolution archetypes and scenario-based simulations to quantify energy-saving and carbon-reduction pathways, thereby establishing a robust physical foundation for policy benchmarking. Research aligned with SDG 11 frequently integrates UBEM outputs with GIS layers, land-use proxies and accessibility indices, illustrating the model's compatibility with urban spatial analysis. Under SDG 12, studies increasingly link building energy models to life-cycle assessment and material-flow accounting, extending the analytical

scope toward circular-economy considerations. Moreover, a growing number of papers adopt Bayesian calibration and Monte Carlo-based uncertainty quantification, marking a gradual shift from deterministic forecasting to probabilistic evaluation [131]. While these developments point to an evolving methodological maturity, it is also important to recognise that core aspects of UBEM workflows, ranging from simulation paradigms to data structures, have already been extensively reviewed in prior literature [16,132–135]. The present review thus refrains from reiterating technical taxonomies, focusing instead on the alignment of modelling practices with sustainability imperatives.

However, methodological fragmentation represents another critical barrier to UBEM's broader impact. The diversity of computational approaches and data requirements across UBEM platforms results in inconsistencies in output quality, making it challenging to compare findings or integrate them into broader urban planning frameworks. This lack of standardisation limits the scalability of UBEM tools, particularly in resource-constrained settings, and complicates efforts to establish partnerships across disciplines and regions, which are central to SDG 17. Furthermore, the heavy reliance on high-quality input data and computational resources makes many UBEM tools inaccessible to stakeholders in under-resourced areas, further reinforcing disparities in energy research and application. Addressing these methodological inconsistencies through standardisation and the development of more adaptable frameworks is essential for ensuring that UBEM can effectively support diverse urban contexts and foster global collaboration.

5.2.4. Limited exploration in life cycle

In addition to these challenges, UBEM's potential contributions to SDG 12, particularly in advancing circular economy principles, remain underexplored. While the field has made strides in promoting energy efficiency and reducing operational energy use, it has largely neglected the life-cycle impacts of building materials and the resource flows associated with urban energy systems. For example, retrofitting and demolition activities generate material waste, yet these aspects are seldom considered in UBEM frameworks. Integrating circular economy principles into UBEM would enable a more comprehensive approach to resource efficiency, aligning the field more closely with SDG 12 and advancing sustainability across the entire life cycle of urban energy systems.

Despite these limitations, UBEM holds immense potential to transform urban energy systems and contribute to a wider array of SDGs. Its technical capabilities provide a strong foundation for addressing energy efficiency and climate resilience, while its integration into urban planning processes has already demonstrated tangible benefits in certain contexts. However, for UBEM to fulfil its potential, a paradigm shift is required in its research priorities. Expanding its geographic focus to include underrepresented regions, standardising methodologies to ensure consistency and comparability, and integrating frameworks that address social equity and collaborative governance are essential steps forward. Moreover, fostering interdisciplinary partnerships and engaging local communities in the decision-making process would enhance UBEM's ability to address the interconnected challenges of urban sustainability holistically.

In conclusion, while UBEM has made remarkable progress in advancing urban-scale building modelling, its contributions remain uneven across the SDGs. Its strong alignment with SDGs 7, 11, 12, and 13 demonstrates its technical strengths in promoting clean energy, sustainable cities, responsible resource use, and climate action. However, its limited engagement with SDGs 1, 9, 10, and 17 underscores the need for a more integrated and inclusive approach. By addressing geographic and disciplinary biases and enhancing methodological consistency, UBEM can evolve into a transformative framework capable of supporting a broader spectrum of SDGs. Such evolution is essential for ensuring that UBEM not only advances technical objectives but also contributes to equitable, inclusive, and sustainable urban development worldwide.

5.3. Future directions in supporting SDGs

UBEM has rapidly become a powerful instrument for promoting sustainability in urban environments, particularly in relation to SDGs 7, 11, 12 and 13. These goals, which are highly pertinent to UBEM, illustrate the method's capacity to optimise energy systems, reduce carbon emissions, and bolster urban resilience. Nevertheless, UBEM's potential for addressing SDGs with more limited relevance, e.g., SDGs 1, 4, 8, 9, 15 and 17, remains underexplored. Moreover, considerable opportunities lie in applying UBEM to SDGs that have received minimal attention to date, such as SDGs 2, 3, 5, 6, 10 and 16, thereby opening a promising avenue for future research. This section delineates prospective research trajectories for UBEM, focusing on consolidating its role in high-relevance SDGs, extending its contributions to SDGs with currently limited engagement, and examining emergent applications in hitherto unexplored SDGs.

5.3.1. Advancing UBEM in SDGs with high relevance

UBEM has already contributed substantially to several SDGs, and preserving this momentum requires further work on enhancing its adaptability, multi-objective functionalities and data-integration strategies.

In relation to SDG 7, UBEM has achieved notable success in modelling the incorporation of renewable energy solutions into urban energy infrastructures. City-level application potential has been explored, such as photovoltaic panels [136] and wind turbines [137]. While existing research often focuses on district-level energy grids, which generate detailed simulations of energy flows [138] and identify pathways for reducing dependence on fossil fuels [139], these models are generally static. Consequently, they lack the capacity for real-time adaptability, which is essential for optimising renewable energy utilisation under changing conditions. Moving forward, the development of dynamic models that draw upon live data streams, for example, IoT-based sensors or inputs from smart grids, could enable ongoing recalibration and optimisation, ensuring UBEM remains adaptive and effective in evolving urban contexts. Parallel contributions have been made to SDG 11 through detailed urban retrofit simulations, which have proven beneficial in raising energy efficiency and reducing operational emissions. Future endeavours could integrate urban morphology [140] or planning factors [141] into holistic UBEM models, thereby enabling more comprehensive evaluations of how the physical layout of cities affects energy demand. This approach would allow planners to propose retrofit strategies that are both building-specific and responsive to localised urban structures. Regarding SDG 12, progress has primarily focused on optimising resource consumption during the operational phase of buildings. However, life-cycle aspects, including the material waste associated with renovation or demolition, are frequently overlooked. Although circular economy concepts have been discussed in relation to urban systems [142], their application within UBEM remains narrow. Thus, research could incorporate life-cycle analyses into UBEM frameworks, moving beyond mere operational optimisation to encompass the holistic environmental effects of buildings. Under SDG 13, UBEM provides a strong foundation for modelling city-wide emissions and evaluating climate-adaptation measures. Nonetheless, there is substantial scope to delve deeper into climate-resilience strategies, such as mitigating extreme weather events or diminishing urban heat islands [22]. Future studies could bridge these gaps through the creation of real-time, adaptable models, the integration of life-cycle viewpoints, and the inclusion of cross-sectoral urban-scale simulations. By resolving these issues, UBEM can continue to be a leading tool for SDGs 7, 11, 12 and 13.

5.3.2. Expanding UBEM in SDGs with limited relevance

While UBEM has historically emphasised environmental and energy-related SDGs, it could meaningfully influence SDGs 1, 4, 8, 9, 15 and 17. Focusing on these goals would increase UBEM's impact and relevance in sustainability discourse.

For SDG 1, UDEM could be harnessed to identify households experiencing energy poverty and to design context-specific measures that mitigate it. Models integrating socio-economic variables, such as income data, residential quality and energy costs, would enable an assessment of policies, including subsidies, retrofitting initiatives, or community-led energy projects. Although some studies have already explored energy accessibility and affordability, most have been restricted to particular regions or high-income nations [15]. More effort is needed to refine tools to evaluate energy poverty at scale, particularly in low-income settings, thereby guiding policymakers to channel resources more effectively to vulnerable communities. Concerning SDG 4, UDEM can improve the energy performance of educational structures in under-resourced areas. Adequate energy provision is indispensable for lighting, climate control and digital learning technologies. By forecasting energy demands and proposing efficiency solutions, UDEM could support cost-effective enhancements that not only minimise energy consumption but also create healthier learning environments. Turning to SDG 8, while numerous studies have demonstrated that retrofitting buildings can generate financial gains [143], further research might include constructing regional models to assess the broader economic ramifications of energy transitions. Such analyses could examine job creation in green industries and the economic stimulus stemming from energy investments, particularly in marginalised areas. With regard to SDG 9, creating specialised modules within UDEM for industrial energy systems would help optimise energy consumption in manufacturing and logistic hubs. Existing research has tentatively explored the energy performance of industrial buildings [144,145], but such efforts often concentrate on individual buildings or single industrial sectors, neglecting the interactions with wider infrastructure systems, for example, transport or logistics. Extending UDEM to entire industrial clusters would reveal opportunities for shared resource usage and cross-sector efficiency gains, and could also clarify how infrastructure projects, such as district heating or transport electrification, contribute to more sustainable urbanisation [146]. For SDG 15, there is scope to investigate the links between energy use and environmental protection. Whilst urban greening interventions, for example green roof [147,148], have been examined for their carbon-sequestration capacity and energy impacts, research into their role within broader, holistic sustainability strategies remains limited. Future studies might integrate biodiversity benefits and urban cooling in a unified UDEM platform. Lastly, SDG 17 highlights the importance of global partnerships, which UDEM could foster by encouraging open-source collaboration and methodologies. Greater sharing of expertise and capacity-building, particularly in low-income regions, would reinforce the worldwide utility and inclusiveness of UDEM. In light of the growing emphasis on equity-oriented goals such as SDGs 1, 4 and 8, future UDEM research could benefit from a more systematic integration of socio-economic data into simulation workflows. This may include coupling building-level energy models with census-derived indicators, such as income brackets, tenancy types, or household vulnerability indices, to support disaggregated scenario analysis. Geospatial integration through GIS or digital twins could further enable spatially resolved assessments of energy burden and retrofit impacts across demographic groups. Additionally, emerging equity metrics such as the energy burden ratio and Gini coefficient offer promising tools to evaluate disparities in energy access and thermal safety. Incorporating participatory modelling processes that engage communities in co-defining retrofit priorities and scenario assumptions would also enhance the social responsiveness of UDEM. Together, these methodological expansions could shift UDEM from a technocratic planning instrument to a more inclusive framework for justice-oriented urban energy transitions. By broadening its remit to encompass SDGs 1, 4, 8, 9, 15 and 17, UDEM would demonstrate its adaptability and extend its reach across a more varied spectrum of sustainability issues.

5.3.3. Unlocking UDEM'S potential in unexplored SDGs

Although UDEM has traditionally concentrated on energy and

environmental concerns, it can also address SDGs 2, 3, 5, 6, 10 and 16, indicating exciting opportunities for further growth. These goals, while not explicitly linked to urban energy systems, correspond to broader sustainability and equity questions that UDEM could help resolve. However, it is also necessary to acknowledge that certain SDGs, such as SDG 14 (Life Below Water), fall outside the feasible scope of UDEM due to their focus on marine ecosystems. In the following, the specific mechanisms, data requirements, and research questions through which UDEM can effectively support these underrepresented goals are explained.

Considering SDG 2, it may not appear closely connected to UDEM at first glance. Nevertheless, incorporating urban agriculture within energy-efficient building configurations offers a promising intersection. UDEM can simulate the energy implications of vertical farms, rooftop gardens and hydroponic systems in urban settings, which certain studies have begun to explore [149,150]. These models can optimise energy use for controlled environments, such as lighting and service systems, enabling cities to produce food sustainably while reducing energy demand. In respect of SDG 3, UDEM can enhance public health by modelling buildings that maintain superior indoor air quality and thermal comfort [151]. Some researchers at the building stock level have examined how indoor temperature conditions influence cognitive performance [152]. UDEM can also test improvements such as advanced ventilation or energy-efficient climate-control systems that diminish respiratory problems and heat-related ailments, in addition to providing energy resilience in hospitals and clinics during extreme weather or power interruptions. SDG 5 constitutes another fertile area for UDEM. By integrating gender-disaggregated data on energy usage, it becomes feasible to identify disparities in access and affordability among different types of households, thus enabling policies that aim for greater equity [153]. Initiatives could, for example, emphasise single working individual households, promoting both economic empowerment and enhanced living conditions. UDEM could similarly inform the design of safe, accessible urban areas that reflect people's particular concerns. Addressing SDG 6, UDEM could consider the energy-water nexus by assessing the energy demands of water-management systems in tandem with water sustainability [154]. Existing studies into urban-level rainwater harvesting [155] and greywater recycling [156] point to notable benefits, especially in water-scarce regions. By unifying these analyses within UDEM, planners can weigh the trade-offs between energy and water priorities more effectively. SDG 10 offers a further dimension, permitting UDEM to evaluate the effects of energy policies on diverse socio-economic cohorts. Such analyses can expose inequities in energy pricing and availability, laying the groundwork for fairer energy policies [157]. Lastly, UDEM can advance SDG 16 by increasing transparency and civic participation in urban energy governance. Participatory modelling approaches enable local communities to engage directly with policy discussions, while also illustrating how various energy interventions might affect social equity. Such clarity fosters trust between the public and decision-makers, encouraging more inclusive and just urban energy transitions. Although UDEM has considerable potential in relation to these SDGs, its relevance to SDG 14 is distinctly limited, as marine conservation and ocean management extend beyond UDEM's terrestrial focus. Tools like oceanographic models or coastal management frameworks are more suited to that domain.

To operationalise the role of UDEM in supporting unexplored SDGs, Table 5 outlines a set of concrete research directions. These include identifying integration challenges specific to these SDGs, highlighting additional data requirements, particularly socio-economic, demographic, and health-related datasets beyond conventional GIS and building data, so as to propose targeted and potential research questions. Together, these elements illustrate the importance of cross-disciplinary collaboration, engaging urban energy modellers, public health experts, and social scientists. Future work is encouraged to adopt a reflexive and participatory modelling perspective, helping to reposition UDEM from a purely technical tool toward a socially attuned platform capable of

Table 5

Challenges, data requirements and possible research questions for UBE in supporting unexplored SDGs.

Unexplored SDGs	Challenge for UBE in Supporting the SDG	Additional data requirement	Possible Research Questions
SDG 2 Zero Hunger	Limited modelling of urban agriculture-energy nexus	Rooftop farm locations, building structural capacity, crop yield models	• How can UBE quantify the energy impact of urban agriculture? • What modelling approaches best capture vertical and rooftop farming systems? • How do indoor environmental conditions influence public health outcomes? • Can UBE support energy-resilient design for health-care facilities? • How does gender influence energy access and use in buildings?
SDG 3 Good Health and Well-being	Weak links between energy and public health outcomes	Age-disaggregated population data, health statistics,	• Can UBE address gender-related disparities in thermal comfort or affordability? • What are the energy implications of urban water reuse systems?
SDG 5 Gender Equality	Unclear relationships between gender and energy use	Gender-disaggregated population and household energy use data	• How can UBE address gender-related disparities in thermal comfort or affordability? • What are the energy implications of urban water reuse systems?
SDG 6 Clean Water and Sanitation	Entangled and complex energy-water nexus	Rainwater and greywater reuse data, urban water system infrastructure	• How can UBE support integrated modelling of energy-water flows? • How do retrofit benefits vary across income groups and housing types?
SDG 10 Reduced Inequalities	Inadequate analysis of socio-economic inequality in energy transitions	Income levels, household characteristics, spatial population distribution	• Can UBE assess spatial and social equity in energy policy impacts? • How can UBE promote civic participation and transparency in energy planning?
SDG 16 Peace, Justice and Strong Institutions	Too technical and inaccessible UBE platforms	None (focus on platform openness and interface accessibility)	• Can it evolve into an open platform for public co-creation and decision support?

enabling more inclusive, transparent, and justice-oriented urban energy transitions.

In conclusion, expanding UBE to encompass SDGs 2, 3, 5, 6, 10 and 16 highlights its breadth as a framework for tackling a wide range of sustainability challenges. Recognising its limitations with respect to SDG 14, future work should concentrate on optimising UBE's contributions in land-based contexts, while also acknowledging the need for complementary approaches in areas that lie outside its scope. Future studies may also consider drawing on conceptual frameworks such as urban metabolism or socio-technical transitions to further explore the systemic role of UBE in enabling long-term urban sustainability transitions.

5.3.4. Translating UBE recommendations into actionable pathways

To move beyond recommendations and foster real-world uptake, clear implementation strategies are needed across the academic, public and technical sectors, explicitly aligning UBE applications with the SDGs to ensure urban strategies are both evidence-based and globally relevant. Within the UBE research community, a practical first step is the publication of open, standardised archetype libraries and geospatial input datasets that include metadata on building function, occupancy schedules and socio-economic conditions. These resources would enable more consistent benchmarking and facilitate transferability across urban contexts. Researchers can further contribute by adopting modular modelling architectures, allowing integration of components such as embodied carbon calculators, equity indicators and scenario management modules without requiring wholesale redevelopment. Widespread adoption also depends on good software practice, including code transparency, documentation and open licensing.

Urban policymakers and planning authorities can embed UBE outputs into operational frameworks by incorporating simulation results into climate adaptation plans, retrofit funding schemes and land-use regulations. Procurement guidelines may require the use of UBE to assess the spatial distribution of energy savings, health co-benefits or cost-efficiency across demographic groups. Governments and international agencies could also fund regional UBE centres to support model deployment in data-scarce environments, offering capacity-building and maintenance functions.

Technical consortia, platform developers and international networks play a critical enabling role. This includes developing and promoting shared data schemas, APIs and lightweight modelling interfaces accessible to non-specialist users. Initiatives such as the IEA Annexes [158], C40 Cities [159] or UNEP-led platforms [160] could serve as convening spaces for methodological alignment and peer validation. These actions would help operationalise the potential of UBE as a policy-relevant tool, supporting urban sustainability agendas with both scientific rigor and practical relevance. These collaborations can strengthen SDG partnerships while accelerating the translation of UBE insights into integrated urban sustainability strategies.

5.4. Linking UBE to broader sustainable development

UBE has emerged as a key analytical tool for evaluating the impacts of building interventions on various SDGs. While many UBE applications focus on individual outcomes, such as reducing operational energy (SDG 7) or lowering emissions (SDG 13), real-world urban systems are far more interconnected. Interventions in the built environment often produce cascading effects across infrastructure networks, social systems, and governance regimes, shaping outcomes that span multiple SDGs simultaneously. To fully capture these interactions, UBE must be understood not only as a technical instrument, but also as part of broader urban systems. Two complementary frameworks could help illuminate these complex dynamics. The first is urban metabolism, which conceptualises cities as dynamic systems governed by flows of energy, water, materials, and waste [161]. The second is socio-technical transitions, which examines how technological change co-evolves with institutions, behaviours, and regulatory structures [162]. These frameworks offer a systems-level foundation for embedding UBE within urban sustainability science, enabling deeper insight into how building-scale interventions influence structural transformation across multiple SDGs.

Urban metabolism views the city as a metabolic organism, continuously processing resources through built, social, and ecological subsystems [163]. Within this framework, buildings are not isolated energy consumers, but embedded components of larger material-energy-waste cycles. UBE contributes to this lens by quantifying energy inputs and outputs at various scales, and, when extended, can incorporate water use, waste heat, embodied carbon, and infrastructure dependencies. By applying urban metabolism thinking, UBE analyses can capture trade-

offs that extend beyond operational performance. For example, improving insulation reduces energy demand (SDG 7, SDG 13) but may increase embodied emissions and material throughput (SDG 12), raising concerns about lifecycle sustainability. Similarly, building electrification can reduce direct fossil fuel use, but shift demand burdens to upstream grid infrastructure or water-intensive energy generation (SDG 6). When spatialised, UBEM allows these flows to be mapped across neighbourhoods or districts, enabling policy to identify metabolic “hotspots” and design interventions aligned with SDG 11 sustainable cities, SDG 9 infrastructure resilience, and SDG 15 terrestrial ecosystems. UBEM’s integration with urban metabolism therefore shifts the modelling focus from efficiency in isolation to systemic resource rebalancing, positioning buildings as metabolic interfaces that shape urban sustainability trajectories.

Socio-technical transitions theory examines how large-scale systemic change occurs through the interplay of technological innovation, user behaviour, institutional inertia, and regime disruption [164]. In this view, UBEM is more than a predictive tool, it is an agent in transition pathways, influencing how energy systems evolve in response to environmental, economic, and political pressures. UBEM enables scenario testing for deep retrofiting, renewable integration, district heating, or net-zero targets, all of which interact with incumbent socio-technical regimes. For example, wide-scale retrofiting simulated through UBEM can drive investment shifts (SDG 8), challenge fossil-dependent heating systems (SDG 7), and expose equity imbalances in access to efficient housing (SDG 1, SDG 10). However, these pathways are socially embedded, and models that ignore tenant-landlord dynamics, policy inertia, or information asymmetry risk misrepresenting feasibility and fairness. Crucially, UBEM applications under this framework must engage not just with physical outcomes but with institutional design, participatory governance, and local knowledge. Community-based data collection, transparency in modelling assumptions, and integration with local planning processes align UBEM with SDG 16 inclusive institutions and SDG 17 partnerships for implementation. Rather than modelling “what is optimal”, UBEM within a socio-technical lens asks what transition is possible, for whom, and under what conditions.

Together, these frameworks reposition UBEM as a system-aware decision support tool capable of navigating cross-SDG dynamics. Urban metabolism highlights the hidden flows and material consequences of building choices [165], while socio-technical transitions foreground questions of equity, governance, and lock-in [166]. A system’s perspective allows UBEM to transcend single-target optimisation and instead support co-benefit identification, conflict anticipation, and long-term urban transformation. Future research should prioritise UBEM approaches that incorporate life-cycle flows, institutional constraints, and spatial justice metrics, thereby aligning modelling practice with the integrated nature of the SDGs themselves.

6. Conclusions

UBEM has emerged as a critical analytical framework for addressing complex sustainability challenges in urban contexts. By enabling high-resolution, city-scale assessments of building energy performance, UBEM provides technical foundations for informed urban planning and policy-making. This review evaluates the extent to which UBEM research aligns with the SDGs, and highlights both its demonstrated strengths and untapped potential in advancing a more inclusive, resilient, and low-carbon urban future. A synthesis of UBEM’s relevance to the SDGs is visualised in Fig. 16, which categorises its contributions into strongly supported, moderately addressed, and future potential goals. This mapping highlights both the established technical strengths of UBEM and the emerging directions for expanding its sustainability impact.

Key takeaways of this study are summarised below.

- UBEM shows robust alignment with SDG 7, SDG 11, SDG 12, and SDG 13, where it supports clean energy transitions, urban decarbonisation, responsible resource use, and climate adaptation. These contributions are facilitated through simulations, scenario modelling, and data integration, particularly in high-income, data-rich urban contexts.
- More recent research extends UBEM’s application to SDG 1, SDG 4, SDG 8, SDG 9, SDG 15, and SDG 17 by linking building performance to socio-economic equity, education, employment, industrial systems, ecological resilience, and collaborative governance. These connections remain emergent and require further methodological consolidation.
- UBEM holds latent potential to support SDG 2, SDG 3, SDG 5, SDG 6, SDG 10, and SDG 16 through innovations such as modelling the energy implications of urban agriculture, indoor environmental quality, gender-disaggregated energy access, water-energy interdependencies, spatial inequality, and participatory decision-making processes.
- Realising these expanded contributions depends on addressing persistent limitations in the field, including methodological fragmentation, limited engagement with life-cycle and equity indicators, and the geographical concentration of case studies in the Global North. These constraints hinder the scalability and inclusivity of current UBEM practices.
- UBEM can be more effectively leveraged to support sustainable development when situated within systems-based frameworks such as urban metabolism and socio-technical transitions, which enable

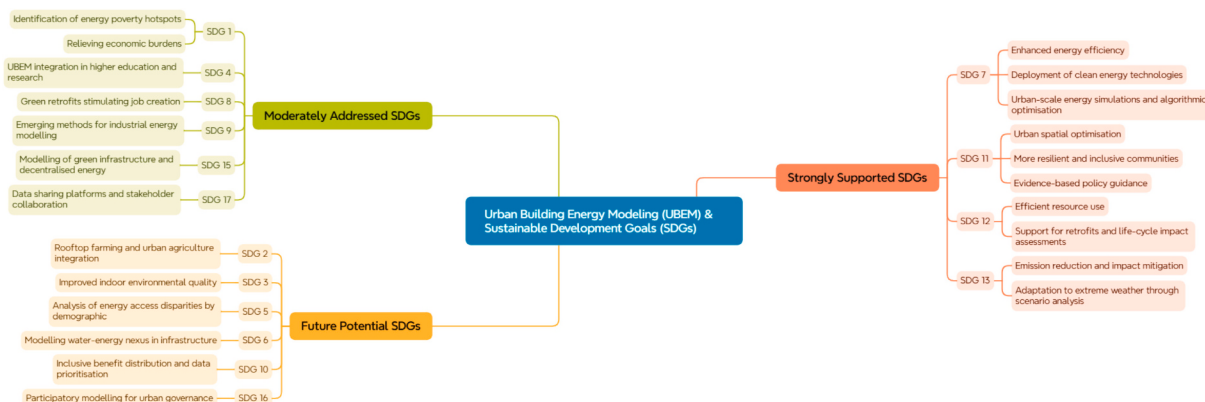


Fig. 16. Summary of UBEM contributions to the SDGs categorised by level of engagement.

more holistic assessment of its multidimensional impacts across broader sustainable developments.

Overall, the evidence reviewed confirms UBEM's capacity to deliver substantial technical contributions to sustainability, yet also reveals clear opportunities for broader impact. Strengthening its role will require moving beyond isolated technical studies toward integrated frameworks that connect energy performance with social equity, health, and environmental resilience. Priority areas for future work include developing standardised modelling protocols to improve comparability, expanding applications to underrepresented regions and SDGs, and embedding UBEM within participatory governance processes to enhance transparency and local relevance. Advancing these agendas can help reposition UBEM from a specialised analytical tool to a globally adaptable platform that informs inclusive, resilient, and low-carbon urban transitions under the 2030 Agenda.

Appendix A. Summary of main established UBEM platforms

Table A1

Summary of main established UBEM platforms.

Platform	Development Team	Computational Core	Functional Overview	Application Scale	Reference
City Energy Analyst	Swiss Federal Institute of Technology Zurich	Reduced-order model	Energy system analysis and optimisation at district and neighbourhood scales.	District/Neighbourhood scale	[8]
CityBES	Lawrence Berkeley National Laboratory	EnergyPlus	Web-based data platform for assessing urban building energy performance.	City-scale	[9]
CitySim	École Polytechnique Fédérale de Lausanne	CitySim Solver	Urban building energy simulation aiming to minimise energy consumption and emissions.	City-scale	[10]
COFFEE	National Renewable Energy Laboratory	EnergyPlus & OpenStudio	Optimises future energy efficiency at the city scale.	City-scale	[167]
Energy Atlas	Technical University of Munich	Reduced-order model	Spatial analysis of urban structures and energy assessment of building clusters.	City-scale	[168]
LakeSIM	Argonne National Laboratory	Reduced-order model	Urban infrastructure modelling to support energy efficiency in new urban developments.	City-scale	[169]
MIT UBEM Tool	Massachusetts Institute of Technology	EnergyPlus	Hourly energy demand calculations across entire cities.	City-scale	[170]
OpenIDEAS	KU Leuven	Modelica-based reduced-order model	Comprehensive energy assessment and analysis at urban and regional scales.	Urban/Regional scale	[171]
SimStadt	Stuttgart University of Applied Sciences	Reduced-order model	Urban energy analysis at the district scale.	District-scale	[172]
SimStock	University College London	EnergyPlus	Automatically generates dynamic building energy simulation models, supporting large-scale parallel simulations and various scenario analyses.	City-scale	[173]
TEASER	RWTH Aachen University	Modelica-based reduced-order model	Energy performance assessment of urban building clusters.	City-scale	[174]
UMI	Massachusetts Institute of Technology	EnergyPlus	Rhino-based modelling for neighbourhood-scale building energy analysis.	Neighbourhood-scale	[11]
UrbanOPT	National Renewable Energy Laboratory	EnergyPlus & OpenStudio	Building energy analysis at the district scale, integrating renewable energy modules.	District-scale	[175]
Virtual EPB	Oak Ridge National Laboratory	EnergyPlus	Automated creation of urban building energy models, assisted by machine learning.	City-scale	[176]

Appendix B. Key Functions of UBEM in Supporting SDGs 1, 4, 8, 9, 15 and 17

Table B1

Key Functions of UBEM in Supporting SDGs 1, 4, 8, 9, 15 and 17.

Specific SDG	Function	How UBEM Supports This SDG
SDG 1 No Poverty	Promote equitable access to affordable energy	- Adopt retrofit measures to reduce energy costs for vulnerable groups. - Retrofit domestic buildings in a more economically viable manner
SDG 4 Quality Education	Promote energy education	- Integrate UBEM research into academic education and training - Develop accessible tools for public education
	Promote engagement of educational institutes	- Develop workflows to support institutional participation in urban energy planning - Use campuses as labs for UBEM research

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Table B1 (continued)

Specific SDG	Function	How UBEM Supports This SDG
SDG 8 Decent Work and Economic Growth	Enhance economic sustainability and feasibility	• Demonstrate economic value through UBEM insights on building insulation. • Analyse UBEM-driven models for sustainable energy policies. • Use UBEM simulations to recommend targeted subsidies.
	Manage cost and risk	• Utilise UBEM to optimise retrofits and align with cost goals. • Identify cost-effective energy-saving measures.
	Provide employment opportunities	• Promoting UBEM-supported energy upgrades, creating jobs in retrofitting and energy modelling.
	Drive energy efficiency and innovation	• Improve energy efficiency through advanced modelling techniques. • Promote scalable methodologies for diverse energy solutions.
SDG 9 Industry, Innovation and Infrastructure	Advance sustainable energy infrastructure	• Optimise infrastructure using AI and digital twin technologies. • Enhance energy infrastructure for both urban and remote areas. • Develop integrated solutions for sustainable energy balance.
	Develop scalable and adaptable frameworks	• Build platforms and tools to support urban-scale energy modelling. • Standardise data integration and simulation methods for scalable applications. • Integrate data frameworks to improve modelling efficiency.
SDG 15 Life on Land	Mitigate environmental impacts	• Model low-carbon heating systems using UBEM to reduce GHG emissions and energy demand. • Assess urban energy-saving strategies with UBEM to minimise environmental impacts. • Propose UBEM-informed urban block designs that balance building density with green spaces, ensuring sustainable land use.
	Strengthen partnerships and stakeholder engagement	• Foster collaboration among residents, policymakers, and governments to drive energy efficiency and renewable energy adoption. • Build partnerships between municipal authorities, data providers, and researchers to integrate energy datasets and enhance policy-making.
SDG 17 Partnerships for the Goals	Build scalable and data-driven frameworks	• Engage multiple stakeholders for the development and implementation of UBEM solutions. • Create adaptable UBEM frameworks for varied urban and climatic contexts. • Use global climate models and archetype-based UBEM for energy planning and retrofitting. • Develop GIS frameworks for collaboration between public and private sectors. • Share UBEM tools to encourage global energy optimisation.
	Enhance knowledge and data sharing	• Offer open-source workflows and GIS-based UBEM tools for cross-disciplinary collaboration. • Promote data standardisation and sharing for scalable and accurate UBEM applications. • Publish frameworks and machine learning methods for collaborative energy planning.

Appendix C. Details of the papers reviewed in this work

Table C1

Summary of papers reviewed in this work. (To avoid confusion between the first two numeric columns, Number is a sequential index used only within this table, while Reference is the numeric-style citation that corresponds to the bibliography entry. The two numbers are independent and may not match, so use the Reference column when citing.)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBEM	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
1	[110]	Energy and Buildings	2017	City	Cambridge, Massachusetts	Bayesian approach to defining and calibrating building archetypes			✓				✓			
2	[177]	Applied Energy	2018	City	San Francisco, California, USA	UBEM framework development			✓							
3	[78]	International Journal of Sustainable Development and Planning ISPRS	2018	Community	Seville, Spain	UBEM framework development			✓			✓				
4	[121]	International Journal of Geo-Information	2018	City	Karlsruhe, Germany	UBEM framework development			✓			✓			✓	
5	[178]	Energy and Buildings	2018	City	Aarhus, Denmark	UBEM framework development			✓							
6	[104]	Energy and Buildings	2019	National	Ireland	UBEM method development			✓			✓	✓	✓		✓
7	[66]	Applied Energy	2019	Community	Massachusetts, USA	UBEM framework development			✓			✓	✓	✓		
8	[53]	Journal of Building Performance Simulation	2019	Community	Massachusetts, USA	UBEM framework development			✓							
9	[77]	Energy	2019	City	Stockholm, Sweden	Development of data-driven archetypes			✓							

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Table C1 (continued)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBE M	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
10	[111]	Journal of Cleaner Production	2019	City	Stockholm, Sweden	Strategic retrofitting framework	✓		✓			✓	✓	✓		
11	[52]	Energy and Buildings	2019	City	San Francisco, California, USA	UBEM framework and data Standardisation			✓			✓				
12	[179]	Applied Energy	2019	Community	Montreal, Canada	Innovative application scenarios						✓		✓		
13	[180]	Energy and Buildings	2019	National	Japan	UBEM method development			✓				✓			
14	[56]	Applied Energy	2020	National	Ireland	UBEM method development			✓	✓		✓	✓			✓
15	[181]	Building and Environment	2020	Community	Zurich, Switzerland	UBEM method development		✓	✓							
16	[63]	Sustainable Cities and Society	2020	Community	Padua, Italy	UBEM method development			✓							
17	[105]	Renewable and Sustainable Energy Reviews	2020	National	EU countries	Application framework development							✓			
18	[72]	Applied Energy	2020	City	San Francisco, USA	UBEM method development			✓							
19	[182]	Energy and Buildings	2020	Community	Berlin, Germany	UBEM method development						✓		✓		
20	[183]	Sustainable Cities and Society	2020	City	Dallas, TX, United States	Innovative application scenarios			✓			✓				
21	[6]	Applied Energy	2020	Regional	Boston, USA, and other urban centers	Development of modelling frameworks and innovative application scenarios						✓		✓		
22	[80]	Energy	2020	City	Aarhus, Denmark	UBEM method development			✓							
23	[184]	Energies	2020	City	Chicago, USA	UBEM method development			✓			✓				
24	[185]	Energies	2020	City	New York City, USA.	UBEM method development						✓		✓		
25	[67]	Energies	2021	Community	Montreal, Canada	UBEM framework development			✓							
26	[75]	Energy and Buildings	2021	Community	Flemish region, Belgium	Data enhancement			✓							
27	[186]	Sustainable Cities and Society	2021	Community	Nanjing, China	UBEM method development										✓
28	[187]	Buildings	2021	City	Boston, United States Aarhus, Denmark	UBEM method development						✓	✓			
29	[125]	Energies	2021	Community	Lodz, Poland	UBEM method development			✓		✓	✓				
30	[76]	Science and Technology for the Built Environment	2021	City	Ahmedabad, India	Application framework development			✓					✓		✓
31	[89]	Climate	2021	City	Padua, Italy	Innovative application scenarios			✓			✓		✓		
32	[58]	Sustainable Cities and Society	2021	Community	Abruzzo region, Italy	Data enhancement			✓				✓			
33	[188]	Energy and Buildings	2021	Community	Aachen, Germany	Development of modelling methods			✓							
34	[107]	Energies	2021	City	Changsha, China	Data enhancement and development of innovative frameworks							✓			✓
35	[189]	Energies	2021	City	Chicago, USA	UBEM method development			✓							
36	[190]	Journal of Cleaner Production	2021	Community	Wuppertal, Germany	Introduced Functional Mockup Interface (FMI)-based			✓							

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Table C1 (continued)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBEM	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
37	[79]	Energy	2021	City	Zurich, Switzerland	urban building energy model Innovative application scenarios			✓			✓				
38	[191]	Building and Environment	2021	Regional	Northern Italy	UBEM method development			✓							
39	[34]	Energy and Buildings	2021	Community	Dublin, Ireland.	UBEM method development			✓			✓		✓		
40	[192]	Journal of Building Performance Simulation	2022	City	California, USA	UBEM framework development						✓				
41	[65]	Sustainable Cities and Society	2022	Community	Beijing, China	Innovative application scenarios			✓							
42	[73]	Journal of Building Engineering	2022	Community	Montreal, Canada	UBEM framework development			✓			✓	✓			
43	[128]	Building Simulation	2022	City	Changsha, China	UBEM method development			✓						✓	✓
44	[193]	Energy and Buildings	2022	National	/	UBEM framework development								✓		
45	[100]	Energy and Buildings	2022	Regional	Salzburg, Austria	Data enhancement			✓				✓	✓		
46	[101]	Energy and Buildings	2022	Community	British Columbia, Canada	UBEM framework development			✓				✓			
47	[194]	Proceedings of the Institution of Civil Engineers: Smart Infrastructure and Construction	2022	City	Germany	UBEM method development			✓							
48	[195]	Energy and Buildings	2022	City	La Rochelle, France	Demand-Side flexibility and sensitivity analysis			✓							
49	[117]	Energy and Buildings	2022	Regional	Boulder, Colorado, USA	Development of hybrid modelling approaches			✓					✓		
50	[102]	Building and Environment	2022	City	Uppsala, Sweden	Framework optimisation and data simplification			✓				✓			
51	[196]	Resources, Conservation and Recycling	2022	City	New York, USA	Development of holistic modelling methods						✓				
52	[36]	Building and Environment	2022	Community	Atlanta, Georgia, USA	Innovative application and data enhancement										✓
53	[197]	Sustainable Energy Technologies and Assessments	2022	Community	Santa Marta district, Venice, Italy	Innovative application scenarios			✓			✓		✓		
54	[108]	Buildings	2022	City	Wuhan, China	UBEM method development and data enhancement			✓				✓			
55	[70]	Renewable Energy	2022	Community	Eastport, Maine, USA	Development of innovative application scenarios			✓			✓		✓		
56	[198]	Energy and Buildings	2022	City	Switzerland	Application framework development						✓				
57	[199]	Energies	2022	Community	Sheffield, United Kingdom	Application framework development and data enhancement			✓				✓			

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Table C1 (continued)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBEM	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
58	[200]	Applied Energy	2022	National	United States	UBEM method development			✓							
59	[201]	Energies	2022	Community	Stockholm, Sweden	UBEM accuracy and fidelity			✓							
60	[202]	Energy and Buildings	2022	City	/	UBEM method development			✓							
61	[55]	Sustainable Production and Consumption International Journal of Architectural Computing	2023	Community	Mumbai, India	New application framework			✓					✓		✓
62	[203]	Solar Energy	2023	City	Sheffield, UK	UBEM framework development						✓				
63	[59]	Sustainable Cities and Society	2023	Community	Benguerir, Morocco not real-world urban stock	UBEM method development			✓			✓	✓			✓
64	[88]	Sustainable Cities and Society	2023	City	Turin, Italy	UBEM method development Innovative application scenarios			✓			✓	✓	✓		
65	[71]	Environmental Research: Infrastructure and Sustainability	2023	City	Oshkosh, Wisconsin, USA	UBEM framework development			✓					✓		✓
66	[62]	Energies	2023	Community	Bolzano, Northern Italy	UBEM framework development			✓	✓		✓				
67	[68]	Energy and Buildings	2023	City	Changsha, China	UBEM method development			✓					✓		✓
68	[112]	Energy	2023	City	Salzburg, Austria	UBEM framework development			✓							
69	[204]	Energy and Buildings	2023	National	France	UBEM framework development			✓							
70	[205]	Environment and Planning B: Urban Analytics and City Science	2023	Community	Boston, Massachusetts, USA	Innovative application scenarios			✓							
71	[206]	Energy and Buildings	2023	City	Seoul, South Korea	Innovative application scenarios			✓			✓				
72	[207]	Environment and Planning B: Urban Analytics and City Science	2023	City	Singapore	UBEM method development						✓				
73	[208]	Applied Energy	2023	National	Bolzano, Italy Messina, Italy Denver, USA	Development of simplification methods Innovative application scenarios and integrated modelling			✓							
74	[209]	Energies	2023	City	Lisbon, Portugal	Development of modelling workflows and application frameworks						✓		✓		
75	[118]	International Journal of Sustainable Energy Planning and Management	2023	Community	Graz, Austria	Assess the impact of climate change scenarios on heating demand		✓				✓		✓		
76	[115]	Environmental and Climate Technologies	2023	City	London, United Kingdom	UBEM framework development			✓		✓					
77	[106]	Journal of Building Engineering	2023	City	Changsha, China	Innovative application scenarios and data enhancement			✓			✓				
78	[84]	Journal of Cleaner Production	2023	City	Beijing, China	UBEM method development						✓				
79	[210]	Sustainable Cities and Society	2023	Community	Hong Kong	UBEM method development						✓				
80	[211]	Energy and Buildings	2023	Community	Tokyo, Japan	UBEM method development			✓			✓	✓	✓		
81	[212]															

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Table C1 (continued)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBEM	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
82	[126]	Energies	2023	Community	Germany	UBEM application framework					✓		✓	✓		
83	[213]	Building Simulation	2023	National	USA	UBEM output enhancement						✓				
84	[214]	Sustainability (Switzerland)	2023	City	Milan	UBEM method development			✓				✓			
85	[215]	Advances in Applied Energy	2023	City	New York City, USA	UBEM method development						✓				
86	[216]	Energies	2023	City	Turin, Italy	UBEM method development			✓							
87	[217]	Energy and Buildings	2023	Community	Nanjing, China	UBEM method development			✓			✓				
88	[218]	Sustainable Cities and Society	2023	City	Sweden	UBEM method development			✓							
89	[219]	Buildings	2023	City	Changsha, China	UBEM method development			✓							✓
90	[220]	Buildings	2023	Community	Barrio das Flores, A Coruña, Spain	UBEM method development			✓							
91	[221]	Energy and Buildings	2023	Community	Lisbon, Portugal	New application framework			✓							
92	[222]	Building Simulation	2023	City	Geneva, Switzerland	UBEM method development						✓	✓	✓		
93	[99]	Building and Environment	2024	Community	University of Singapore (NUS) campus, Singapore	UBEM method development							✓			
94	[87]	Energies	2024	City	Shanghai, China	UBEM framework development						✓		✓		✓
95	[60]	Journal of Architectural Engineering	2024	Community	Mumbai, India	UBEM method development			✓			✓	✓	✓		✓
96	[61]	Energy and Buildings	2024	Community	Nanjing, China	UBEM method development			✓							
97	[74]	Applied Energy	2024	Community	Xi'an, China	UBEM method development			✓							
98	[57]	Advances in Applied Energy	2024	Community	Huntington Beach, Southern California	Innovative application scenarios			✓		✓	✓				
99	[54]	Buildings	2024	City	Pittsburgh, Pennsylvania, USA	UBEM framework development			✓	✓		✓	✓	✓		
100	[127]	Building Simulation	2024	City	Nanjing, China	UBEM framework development	✓	✓				✓				
101	[7]	Applied Energy	2024	City	Varberg, Sweden	UBEM framework development			✓				✓			
102	[64]	Energies	2024	Community	Shenzhen, China	UBEM method development			✓							✓
103	[51]	Journal of Building Engineering	2024	City	Manhattan, USA	UBEM method development			✓			✓				
104	[91]	Energy and Buildings	2024	Community	Tartu, Estonia	UBEM framework development						✓				
105	[223]	Energy and Buildings	2024	City	Chicago, USA	Data enhanced			✓			✓				✓
106	[98]	Building and Environment	2024	City	Montreal, Canada	UBEM framework development			✓		✓	✓	✓			✓
107	[113]	Sustainable Cities and Society	2024	City	Shanghai, China	Data integration and automation			✓			✓		✓		
108	[114]	Energy and Buildings	2024	City	Wellington, New Zealand	Dynamic Modelling and degradation effects			✓			✓		✓		
109	[224]	Journal of Building Engineering	2024	City	Changzhou and Nanjing in Jiangsu Province, China	UBEM method development			✓							
110	[225]	Sustainable Cities and Society	2024	City	Hangzhou, China	UBEM framework development						✓				
111	[119]	Energy and Buildings	2024	City	New York City, United States	Innovative application scenarios			✓			✓		✓		

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Table C1 (continued)

Number	Reference	Journal	Published Year	Spatial Scale	Study Location	Focus of UBEM	Related SDGs									
							1	4	7	8	9	11	12	13	15	17
112	[226]	Energy and Buildings	2024	Community	Stockholm, Sweden	UBEM method development			✓							
113	[86]	Renewable Energy Focus	2024	City	Benguerir, Morocco	UBEM framework development			✓		✓	✓		✓		✓
114	[120]	Applied Energy	2024	City	Chicago, Illinois, USA	UBEM framework development			✓			✓		✓		
115	[116]	Energy Efficiency	2024	Community	Politecnico di Torino central campus, Turin, Italy.	Data-enhanced occupancy modelling for UBEM		✓	✓			✓		✓		
116	[227]	Sustainable Cities and Society	2024	City	London, Berlin, New Delhi, and Queretaro	UBEM method development			✓			✓	✓			
117	[83]	Building and Environment	2024	Community	Downtown Montreal, Canada	Data-enhanced occupancy modelling for UBEM						✓		✓		
118	[228]	Energy	2024	Regional	Pakistan (Gilgit, Islamabad, Karachi, Quetta)	UBEM method development			✓			✓	✓			✓
119	[103]	Journal of Building Engineering International Journal of Sustainable Energy Planning and Management	2024	Regional	Bilbao, Madrid, Burgos (Spain)	UBEM method development			✓				✓			
120	[92]	Journal of Building Performance Simulation International Journal of Sustainable Energy Planning and Management	2024	Community	Trento, Italy.	Application Framework Development			✓	✓						
121	[229]	Journal of Building Performance Simulation International Journal of Sustainable Energy Planning and Management	2024	City	Los Angeles, USA	UBEM method development						✓				
122	[122]	Journal of Sustainable Energy Planning and Management	2024	City	Vietnam	Application framework		✓	✓	✓				✓		✓
123	[230]	Building and Environment	2024	City	Basel, Switzerland, Toulouse, France, and Vancouver, Canada	UBEM method development						✓				
124	[231]	Energy and Buildings	2024	City	New York, USA	UBEM method development			✓							
125	[82]	Energy and Buildings	2024	National	United States (eight representative cities)	UBEM method development			✓			✓				
126	[147]	Applied Energy	2024	City	Xiamen, China	Assessing green roofs			✓			✓	✓			✓
127	[81]	Buildings	2024	Community	Renca, Santiago, Chile	UBEM method development			✓			✓		✓		✓
128	[124]	Mathematical Modelling of Engineering Problems Smart and Sustainable Built Environment	2024	City	Turin, Italy	UBEM approaches Comparative analysis		✓	✓	✓	✓				✓	✓
129	[93]	Smart and Sustainable Built Environment	2024	Community	Mumbai, India	New application framework			✓	✓		✓		✓		
130	[109]	Energy and Buildings	2024	City	Dublin, Ireland	UBEM method development			✓				✓			✓
131	[69]	Energies	2024	Community	Corvo Island, Azores, Portugal	Innovative application of tools			✓		✓		✓			
132	[90]	Energy and Buildings	2024	Community	Bauhaus-Universität Weimar	UBEM method development						✓				
133	[85]	Applied Energy	2025	City	Melbourne, Australia	Innovative application scenarios			✓			✓				
134	[123]	Applied Energy	2025	Regional	Flanders region, Belgium	Innovative application scenarios			✓	✓		✓				

Data availability

No data was used for the research described in the article.

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