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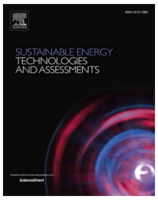

Review article

Urban energy management in historic cities: a critical review of research pathways, technological trends, and future directions

Xiaojia Zhang [a], Elena Lucchi [b,*], Andrea Garzulino [a]

[a] *Politecnico di Milano, Department of Architecture and Urban Studies (DAStU), Italy*
[b] *Università di Pavia, Dipartimento di Ingegneria Civile e Architettura (DICAr), Italy*

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ABSTRACT

The acceleration of urbanisation and the escalating impacts of climate change have elevated urban energy management (UEM) to a critical priority of sustainable development agendas. Historic cities, with their dense concentration of cultural heritage assets and often thermally inefficient building stocks, offer significant opportunities for energy efficiency improvements. Yet, UEM in historic urban environments remains under-investigated. This study provides a critical review of UEM in historic cities, combining bibliometric analyses to trace the field's developmental trajectory, scientometric analyses to identify key research areas and thematic clusters, and thematic analyses of influential studies within these clusters. It identifies five dominant thematic areas (sustainable development, climate change, energy efficiency, renewable energy, and circular economy) and reveals a growing convergence around digital transformation and multi-sensor diagnostic systems. It also outlines three strategic pathways for future research and practice related to: (i) the transition from isolated pilot projects to interoperable, scalable infrastructures, (ii) the evolution from technical-centric approaches to integrated frameworks that embed ethics, governance, and social equity; and (iii) the shift from top-down planning to community-informed implementation models. The integration of Artificial Intelligence, machine learning, and advanced sensing technologies with heritage conservation principles is identified as a transformative frontier for achieving energy resilience without compromising cultural value. By articulating these trajectories, the paper establishes a research agenda to guide the next generation of UEM strategies for historic cities.

Introduction

Nowadays, more than half of the world's population resides in urban areas, and this share is projected to rise to 68% by 2050 [1]. Urban areas consume between 60% and 80% of the world's total energy and are responsible for approximately 75% of global carbon emissions [2]. Projections suggest that global average temperatures will rise by 1.0 °C–3.7 °C by the end of the 21st century, compared to the baseline period of 1986–2005 [3]. This warming trajectory presents multifaceted threats to urban sustainability, affecting infrastructure resilience, public health, resource availability, and cultural preservation. Urban impacts include rising sea levels, intensified urban heat island effects, more frequent extreme weather events, and accelerated degradation of ecosystems, landscapes, and built heritage [4,5].

In response to these challenges, Urban Energy Management (UEM) has emerged as a global priority. Policies and regulatory frameworks have been adopted across countries to promote energy efficiency, renewable energy integration, nearly zero-energy buildings, and large-scale renovations [6–9] as key strategies for achieving long-term climate and carbon neutrality goals [10]. China announced its “*dual*

Abbreviations: AI, Artificial Intelligence; ARCH, Adaptive Reuse of Cultural Heritage; BIM, Building Information Modeling; CBDM, Climate-Based Daylight Modelling; CH, Cultural Heritage; CHVI, Composite Heat Vulnerability Index; DT, Digital Twin; EO, Earth Observation; GIS, Geographic Information System; GPR, Ground-Penetrating Radar; HBIM, Historic Building Information Modelling; ICT, Information and Communication Technology; IoT, Internet of Thing; IRT, Infrared Thermography; LCA, Life Cycle Assessment; LST, Land Surface Temperature; NCC, National Construction Code; NDBI, Normalized Difference Built-up Index; NDVI, Normalized Difference Vegetation Index; NDT, Non-Destructive Testing; PRISMA, Preferred Reporting Items for Systematic Reviews and Meta-Analyses; REC, Renewable energy Community; RES, Renewable Energy Source; SDG, Sustainable Development Goal; TITLE-ABS-KEY, Titles, Abstracts, Keywords; UAV, Unmanned Aerial Vehicle; UEM, Urban Energy Management; UHI, Urban Heat Island; UN, United Nations; WoS, Web of Science; 2D, Two Dimensions; 3D, Three Dimensions.

[*] Corresponding author.

E-mail address: elena.lucchi@unipv.it (E. Lucchi).

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carbon" target, which strives to peak CO_2 emissions by 2030 and achieve carbon neutrality by 2060 [11–14]. It also defines an array of complementary measures for the energy sector and urban development [15]. Australia aims to achieve a carbon–neutral built environment by 2050 through enhanced energy efficiency standards in the National Construction Code (NCC) [16–18]. Besides, the 2030 Agenda for Sustainable Development, adopted by all United Nations (UN) members in 2015, explicitly addresses urban sustainability through Sustainable Development Goals (SDGs) 11 "*Sustainable Cities and Communities*" and 7 "*Affordable and Clean Energy*".

Within this broader urban context, historic cities, characterized by centuries-old and dense heritage buildings, represent a unique and complex challenge for energy management [19]. They serve as both a driver and a practical instrument for the UEM decision-making process [20]. Despite their energy inefficiencies related to poor insulation and outdated systems, they hold significant potential for improvement through targeted retrofitting [21]. They contain considerable amounts of embodied energy that are lost through demolition and replaced with new emissions from redevelopment projects [22]. Conversely, their preservation and adaptive reuse can significantly reduce life-cycle energy consumption and mitigate carbon emissions compared to new constructions [23]. Furthermore, traditional buildings frequently incorporate vernacular design strategies that passively adapt to local climatic conditions [24]. Although heritage buildings may appear unique, they share recurring features shaped by urban morphology, architectural typology, traditional construction techniques, and local environmental conditions [25].

The primary challenge in energy retrofitting for heritage buildings is balancing energy efficiency with the preservation of heritage values, a difficulty widely recognized in the literature [26]. Heritage value is a non-renewable resource and therefore requires consideration equal to that of energy-performance goals [27]. However, achieving this balance is challenging because conservation requirements often conflict with thermal comfort and energy cost reduction, and retrofitting measures may also affect the building's physical integrity and broader environmental performance [26–28]. To address these tensions, Piderit et al. proposed an integrated framework combining heritage, energy, and pathological diagnostics to support decision-making in energy-vulnerable contexts [29]. They argue that compatibility between preservation and efficiency is possible but requires careful weighing of heritage values [30]. Similarly, Roberti et al. developed a quantitative multi-objective optimization method to identify optimal retrofit strategies, demonstrating that heritage preservation can meet strict energy and comfort requirements, although higher efficiency levels may compromise cultural significance [31]. The architectural complexity of historic buildings further constrains intervention choices, increases costs, and reduces economic feasibility, often leading stakeholders to prioritize energy savings over heritage values [26,29]. In addition, strict conservation regulations often limit invasive interventions and restrict technological applications [32,33]. Therefore, effective UEM in historic cities must go beyond the building scale to consider city-wide strategies that respect historical cohesion and urban identity [25]. The integration of energy infrastructures is also critical, requiring a shift from fragmented assessments toward comprehensive management approaches [34]. Recent advances in information and communication technologies (ICT) and non-destructive testing (NDT), including unmanned aerial vehicles (UAVs) and digital platforms, have improved the assessment and management of energy performance in historic urban environments [35,36]. These tools allow for integrated analysis across energy domains and help with a more comprehensive understanding and management strategies of urban energy systems [37]. Despite recent advancements, large-scale implementations are limited [37]. Similarly, although UEM in historic contexts has gained growing importance [38], a comprehensive understanding of the topic remains fragmented and underdeveloped [39]. To address this gap, this review critically examines the scientific literature on UEM in historic cities, with the aim of providing a comprehensive overview of historical evolutions, dominant research themes in current discourse, methodological approaches, technological trends, opportunities, risks, and challenges. Accordingly, this study addresses the following research questions (RQ):

- RQ1: *How has the scientific literature on UEM in historic cities evolved in terms of volume, scope, and disciplinary contributions?*
- RQ2: *What are the dominant research themes, methodological approaches, and technological trends that characterize recent work on UEM in historic cities?*
- *RQ3: What are the main opportunities, risks, and challenges associated with implementing effective urban energy management strategies in historic cities?*

Research methodology

The study adopts a three-step method:

- Bibliometric analysis to map the development trajectory of the field.
- Scientometric analysis to identify key research areas and thematic clusters.
- Thematic analysis of influential contributions within each cluster.

This approach facilitates the analysis of thematic developments over time, the extent of diffusion and dispersion, and the overall status of UEM research within the heritage sector. The search methodology comprises the four key steps (Fig. 1):

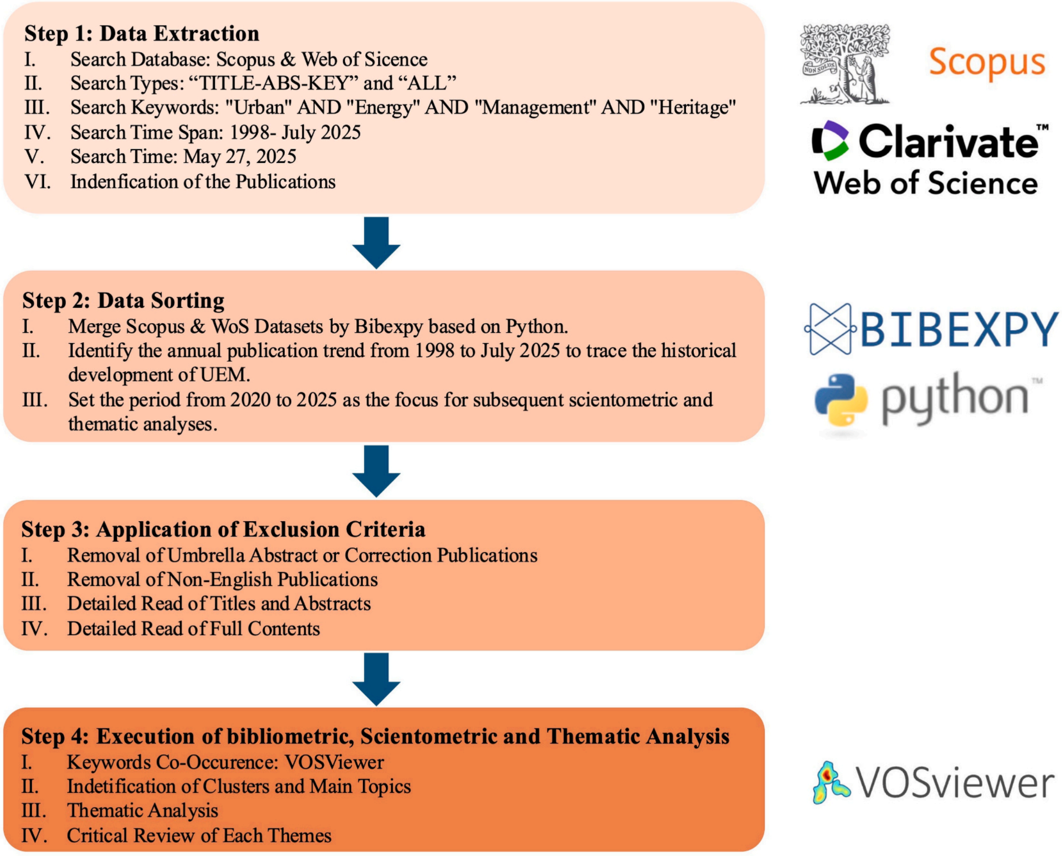
- Data extraction (Section 2.1).
- Data sorting (Section 2.2).
- Application of selection criteria (Section 2.3).
- Execution of scientometric and thematic analyses (Section 2.4).

Data extraction

Data extraction includes all relevant studies published up to July 2025, retrieved from two major bibliographic databases: Scopus and Web of Science (WoS). These repositories were selected for their well-documented complementary strengths: Scopus offers access to a wider range of academic journals, whereas WoS offers more extensive historical indexing [40,41]. In line with established bibliometric protocols [42], an identical search strategy was executed independently within each database. The resulting datasets were subsequently merged, and duplicate entries were removed. A structured screening was then performed to validate both the relevance and the internal coherence of the final selection.

The search employed the keywords *"Urban", "Energy", "Management", and "Heritage"*, combined with the Boolean operator AND to ensure thematic specificity and alignment with the research objectives. The operator OR was tested but excluded because it generated too many off-topic records. Significant discrepancies emerged between Scopus and WoS in terms of search behavior and output. In Scopus, the most effective approach was to apply the TITLE-ABS-KEY (title, abstract, and keywords) filter, which returned relevant and manageable results. Conversely, the ALL search fields introduced considerable noise due to the inclusion of many non-pertinent results. For this reason, only TITLE-ABS-KEY results were retained [43]. In WoS, the TOPIC search returned few or no records, a pattern that can be attributed to more restrictive indexing practices of the platform [40]. Consequently, the ALL FIELDS option was adopted to include the KeyWords Plus features. The results are summarized below (Table 1).

This search strategy ended up in 171 results from Scopus and 269 results from WoS, spanning the period from 1998 to 2025. These datasets were then merged, resulting in 371 unique records after removing 69 duplicates. The integration of Scopus and WoS datasets was



Step 1: Data Extraction

I. Search Database: Scopus & Web of Sicence
II. Search Types: “TITLE-ABS-KEY” and “ALL”
III. Search Keywords: "Urban" AND "Energy" AND "Management" AND "Heritage"
IV. Search Time Span: 1998- July 2025
V. Search Time: May 27, 2025
VI. Indenfication of the Publications

Step 2: Data Sorting

I. Merge Scopus & WoS Datasets by Bibexpy based on Python.
II. Identify the annual publication trend from 1998 to July 2025 to trace the historical development of UEM.
III. Set the period from 2020 to 2025 as the focus for subsequent scientometric and thematic analyses.

Step 3: Application of Exclusion Criteria

I. Removal of Umbrella Abstract or Correction Publications
II. Removal of Non-English Publications
III. Detailed Read of Titles and Abstracts
IV. Detailed Read of Full Contents

Step 4: Execution of bibliometric, Scientometric and Thematic Analysis

I. Keywords Co-Occurence: VOSViewer
II. Indetification of Clusters and Main Topics
III. Thematic Analysis
IV. Critical Review of Each Themes

Fig. 1. Research methodology workflow (source: Authors' elaboration).

Table 1
Search strategy and selected results (in red colour, 27 May 2025): Scopus (n = 171) & WoS (n = 269) (source: Authors' elaboration).

Search query	Scopus		Web of science	
	ALL	TITLE-ABS-KEY	All fields	Topic
“Urban” OR “Energy” OR “Management” OR “Heritage”	34,243,196	13,199,389	12,848,437	9,095,964
“Urban” AND “Energy” AND “Management” AND “Heritage”	26,351	171	269	93

Source: Authors’ elaboration

facilitated using the BibexPy tool, which is specifically designed to support the merging and deduplication of bibliometric records from both databases [41].

Data sorting

To highlight the research focus of this study, all 371 articles retrieved between 1998 and 2025 were systematically organised and analysed. The annual publication trend was examined to reconstruct the historical evolution and the broader research trajectory of UEM in historic cities. The earliest identifiable contribution dates back to 1998. Since then, the development of this research topic can be broadly divided into three phases:

- Phase 1: Slow Exploratory Phase (1998–2011)
- Phase 2: Stable Development Phase (2012–2019).
- Phase 3: Rapid Development Phase (2020-Present).

As depicted in Fig. 2, the initial phase (1998–2011) was characterised by limited scholarly activity, with only sporadic publications and several years entirely devoid of output. Beginning in 2012, the annual production stabilised within a relatively narrow range (9 to 18 articles per year). This reflects the onset of a more structured and steady development of the research domain. A substantial shift occurred in 2020, signalling the beginning of the rapid growth phase. Between 2020 and 2025, the average number of annual publications exceeded 30, and the cumulative output during this period alone accounted for more than half of the total dataset. This acceleration reflects a profound qualitative transformation in the field. The most recent six-year window captures a decisive wave of technological innovation in sensing systems, high-resolution urban energy modelling, integrated digital platforms for heritage monitoring, and advanced NDT techniques that have significantly reshaped the methodological and conceptual tools available to scholars (Fig. 2).

In the last 6 years, 195 papers were published, accounting for 53% of the 371 retrieved articles (Fig. 3).

Accordingly, 2020 was selected as the temporal threshold for the scientometric and thematic analyses. Scientometric and thematic analyses were subsequently conducted on literature published between 2020 and 2025.

Application of selection criteria

The 195 records were subjected to document screening following the Preferred Reporting Items for Systematic Reviews and Meta-Analyses (PRISMA) framework to ensure methodological rigor and transparency. The workflow was structured according to PRISMA’s four key phases: identification, screening, eligibility, and inclusion (Fig. 4), which allowed for a traceable and reproducible filtering of the evidence base. During the screening and eligibility assessment, several records

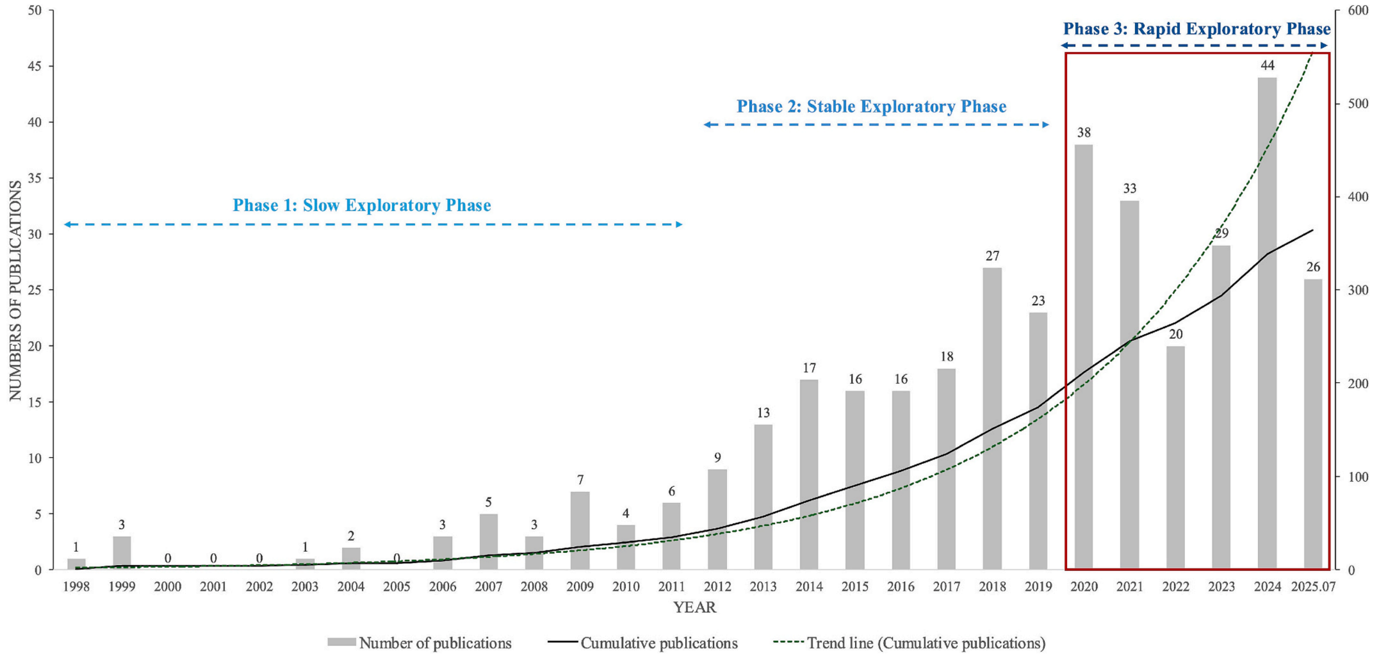


Fig. 2. Yearly trend in research publications (source: Authors' elaboration).

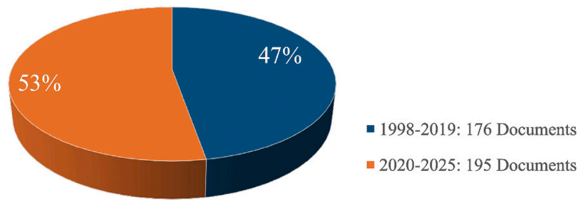


Fig. 3. Comparative Publication Volume: Pre-2020 vs. 2020–2025 (source: Authors' elaboration).

were excluded for specific reasons: Four non-English records, eight umbrella abstracts without accessible full texts were excluded. One corrected duplicate version was eliminated to avoid redundancy, and twenty records that could not be retrieved based on title and abstract were therefore excluded. Three reviewers independently performed the full-text evaluation to ensure methodological robustness and inter-reviewer consistency. This process resulted in the exclusion of an additional 127 records: 49 studies focused solely on the building scale, including single-building adaptive reuse, building-level energy performance and retrofitting, project-based digitalisation applications, and material or structural investigations; 38 records did not involve a heritage context, and 40 lacked relevance to energy-related topics. Ultimately, 35 studies met all inclusion criteria and were retained for the final review. These criteria ensured strict alignment with the scope of UEM in historic cities and supported the synthesis of evidence relevant to the dynamics of heritage urban environments.

Execution of scientometric and thematic analyses

This section covers two main stages of the analysis: (i) the scientometric analysis to identify the most active and thematically concentrated segment of the literature [44]; and (ii) the thematic interpretation of the results. The scientometric analysis was conducted using VOSviewer. It was performed on 'all keywords', applying the 'co-occurrence' type with 'full counting' method to visualize relationships among key terms and to identify thematic clusters and core research areas [45]. A minimum threshold of two keyword occurrences was set, resulting in the selection of 41 terms from an initial pool of 273. To improve the consistency of the network, a VOSviewer thesaurus file was created to consolidate synonymous or variant terms (e.g., "historic centre", "historic center", and "historic centres"), and six geographically generic terms (e.g., "Mediterranean" and "Saudi Arabia") were excluded. The final network included 35 terms grouped into five clusters connected by 133 co-occurrence links.

The thematic analysis is carried out on the five identified clusters to examine the current state of research, reveal knowledge gaps, evaluate the potential applications of innovative NDTs, and highlight existing limitations in the field.

Methodological limitations

Despite the methodological rigor of the review, several limitations should be acknowledged. First, the reliance on Scopus and Web of Science, although consistent with established bibliometric standards, inevitably constrains the evidence base to indexed journals, potentially excluding relevant regional and specialised studies [46]. Second, the exclusive inclusion of English-language publications introduces linguistic bias, particularly affecting research from contexts where historic urban environments are central to energy-transition policies [47]. Third, classification studies into building-scale versus urban-scale categories necessarily involve interpretive judgement, despite being based on explicit criteria, especially for hybrid contributions operating across multiple spatial scales [48]. These limitations do not compromise the internal validity of the review but delineate the boundaries within which the findings should be interpreted. A further limitation concerns the exclusion of studies operating strictly at the building scale. While some of these works may contain insights with potential relevance for multi-building contexts, our scope required a focus on studies that directly engage with district- or urban-scale processes. We acknowledge that this choice may omit certain transitional contributions; however, it preserves the conceptual alignment necessary for analysing UEM strategies applicable to historic cities.

Results of the scientometric analysis

The keyword co-occurrence network revealed five distinct thematic clusters (Fig. 5):

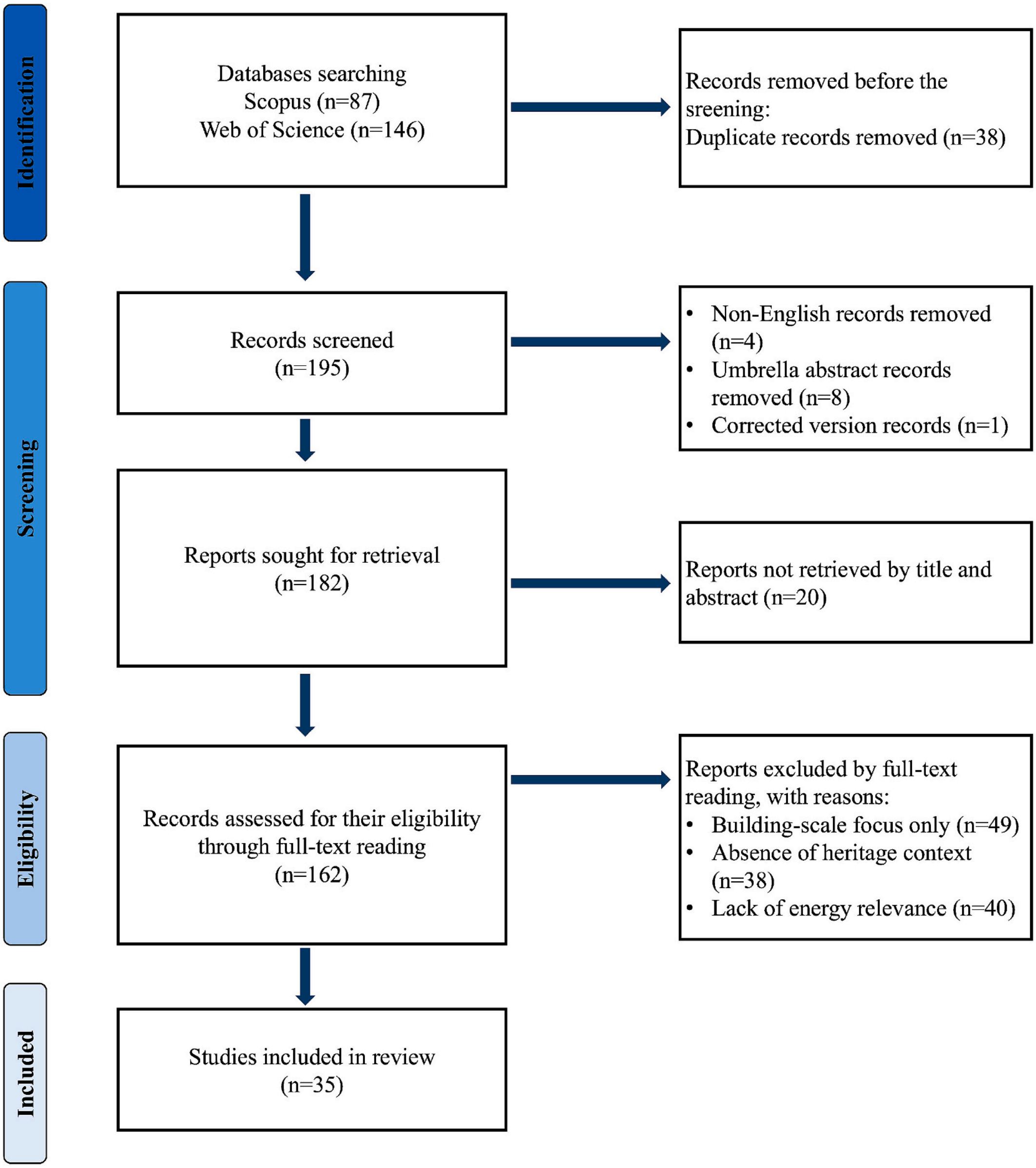


Fig. 4. PRISMA selection flowchart (source: Authors' elaboration).

- Cluster 1 includes keywords such as '*sustainable development*', '*historic centre*', and '*digital twin*', reflecting research focused on sustainable development strategies within historic cities (Section 3.1).
- Cluster 2 comprises terms such as '*climate change*', '*city*', '*heat island*', and '*thermal comfort*', indicating studies centred on urban-scale climate mitigation and adaptation strategies, with particular attention to the urban heat island effect and thermal comfort (Section 3.2).
- Cluster 3 features keywords like '*circular economy*', '*economics*', and '*urban policy*', highlighting an emphasis on circular economy strategies and policy frameworks within the context of UEM (Section 3.3).
- Cluster 4 includes terms such as '*energy efficiency*', '*historic built environment*', and '*web-platform*', describing efforts to enhance energy efficiency, especially in relation to the historic built environment (Section 3.4).
- Cluster 5 incorporates keywords such as '*renewable energy*' and '*urban landscape*', pointing to the role of renewable energy integration in advancing UEM objectives (Section 3.5).

The Density of Keywords Co-occurrence Networks in VOSviewer is an effective tool for identifying thematic concentrations and intellectual structures within scholarly literature (Fig. 6). By visualizing the frequency and co-occurrence of keywords, the density map highlights areas of high research intensity through colour gradients, revealing actively explored topics and their connections. This method is particularly useful for detecting emerging trends, research gaps, and the conceptual landscape of a field.

The total number of occurrences and link strengths for each keyword, along with a summary of the corresponding thematic clusters (Fig. 7).

Sustainable development

Urban energy strategies are closely aligned with SDG 7 (Affordable and Clean Energy), SDG 11 (Sustainable Cities and Communities), and SDG 13 (Climate Action), highlighting the importance of effective urban energy governance. SDG 11 further emphasizes the protection of cultural and natural heritage within urban development, calling for cities and human settlements to become "inclusive, safe, resilient, and

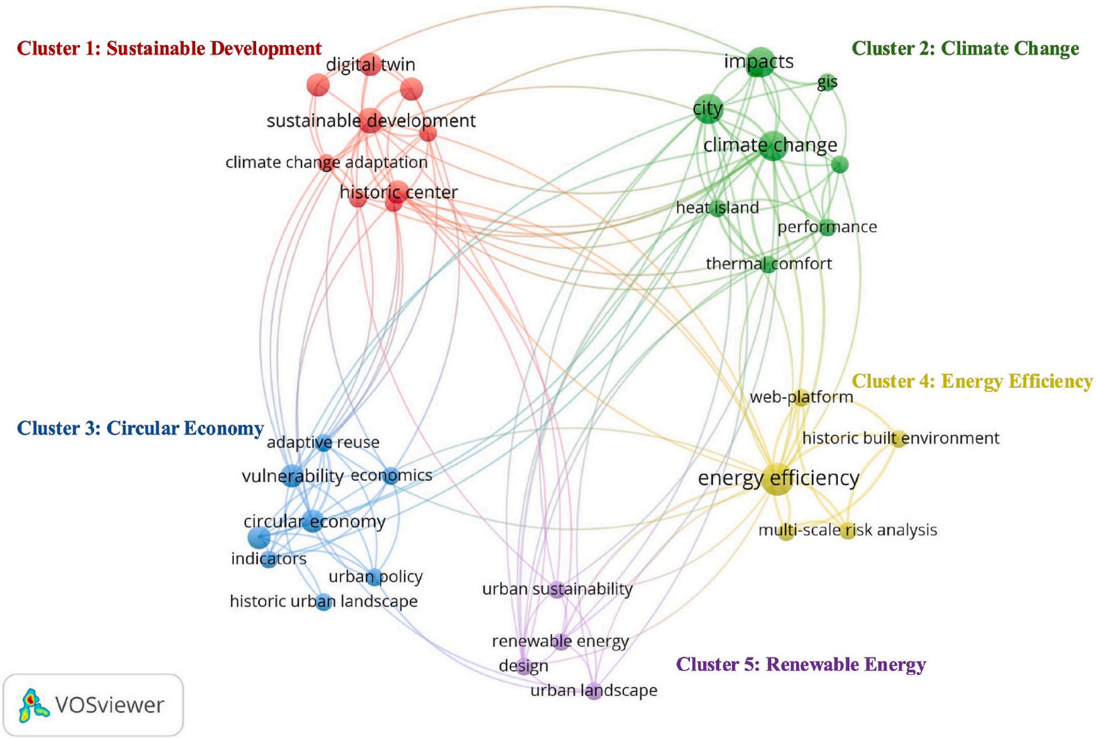


Fig. 5. Visualisation of keywords co-occurrence networks. Cluster colors represent thematic areas: Cluster 1 (Sustainable Development, red), Cluster 2 (Climate Change, green), Cluster 3 (Circular Economy, blue), Cluster 4 (Energy Efficiency, yellow), and Cluster 5 (Renewable Energy, purple) (source: Authors' elaboration with VOSviewer).

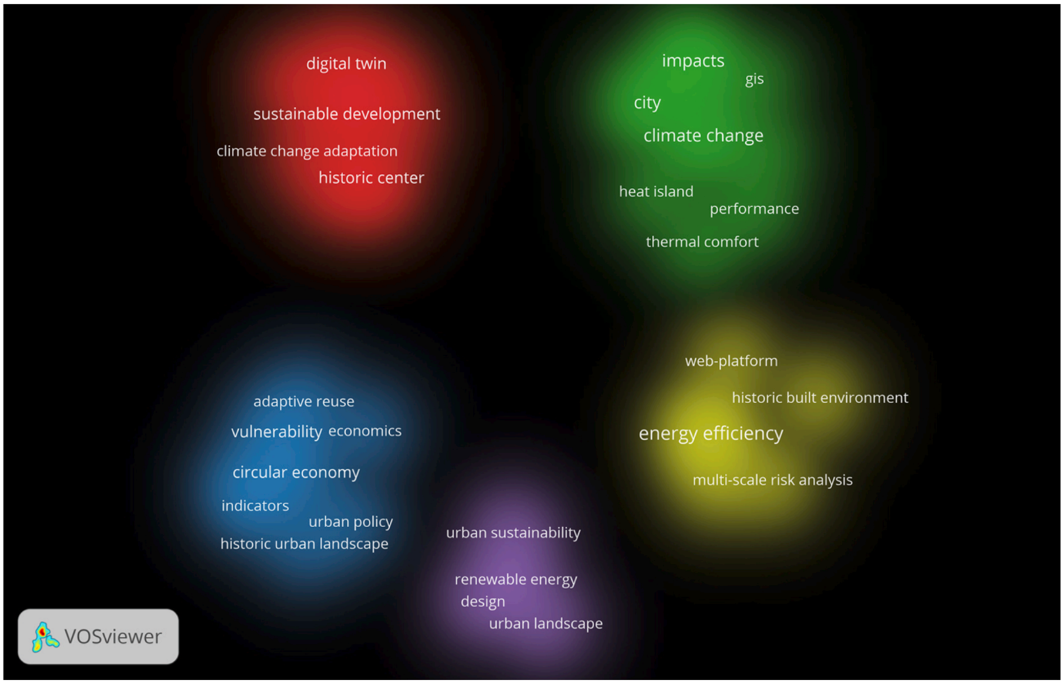
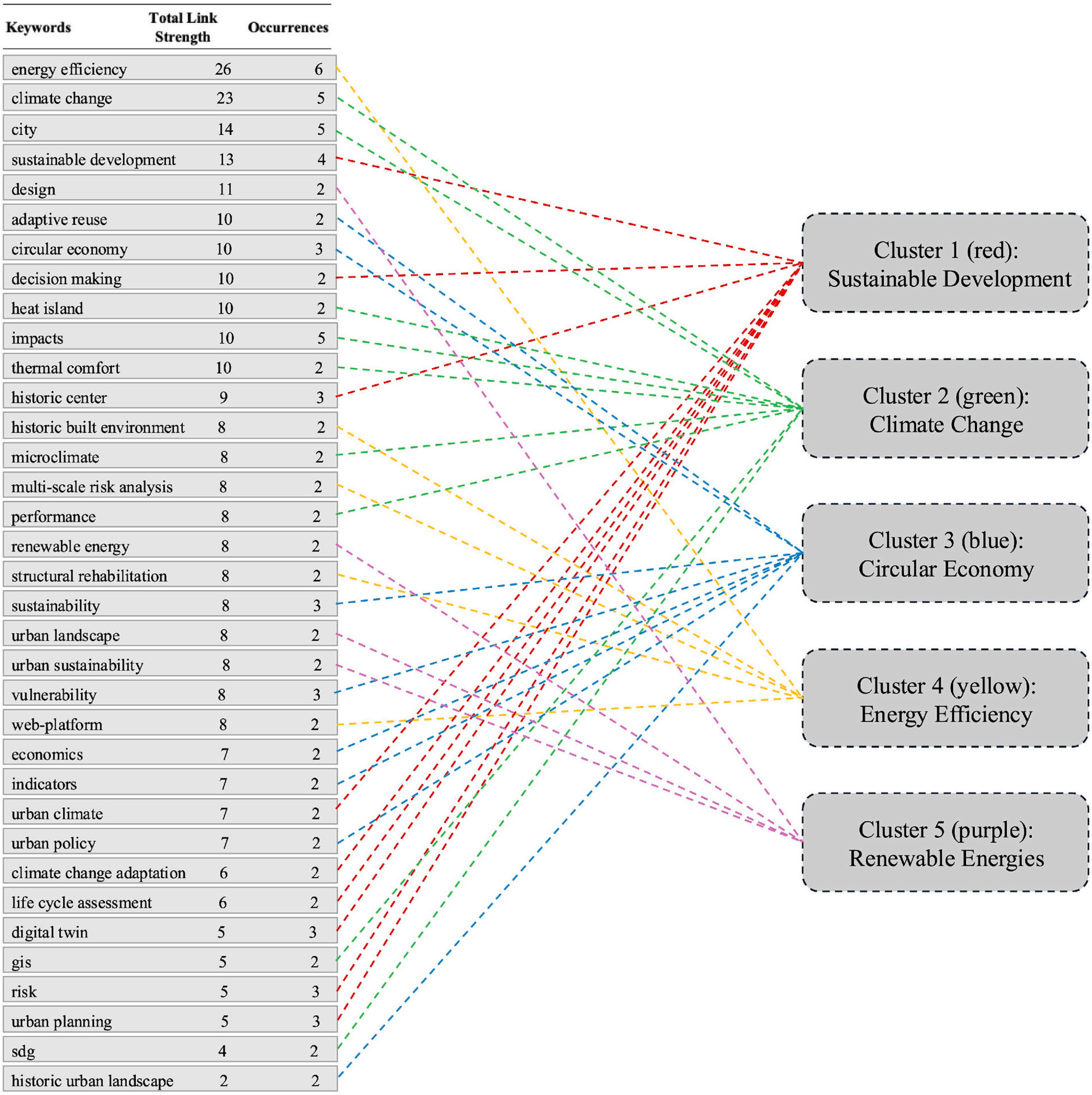


Fig. 6. Density of keywords co-occurrence networks. Cluster colors represent thematic areas: Cluster 1 (Sustainable Development, red), Cluster 2 (Climate Change, green), Cluster 3 (Circular Economy, blue), Cluster 4 (Energy Efficiency, yellow), and Cluster 5 (Renewable Energy, purple) (source: Authors' elaboration with VOSviewer).

sustainable" [2]. Cultural heritage should be integrated into decision-making processes to promote sustainable urban development [20,49] as it contributes to urban identity, landscape continuity, and aesthetic value [50,51]. Historic cities, as integral elements of urban environments, embody both architectural and cultural heritage while simultaneously presenting unique opportunities and challenges for UEM. They often comprise numerous traditional and historic buildings that are highly sensitive to climate and typically lack adequate thermal insulation, thereby presenting significant opportunities for energy efficiency improvements [10,21,52]. However, conservation regulations



Keywords	Total Link Strength	Occurrences
energy efficiency	26	6
climate change	23	5
city	14	5
sustainable development	13	4
design	11	2
adaptive reuse	10	2
circular economy	10	3
decision making	10	2
heat island	10	2
impacts	10	5
thermal comfort	10	2
historic center	9	3
historic built environment	8	2
microclimate	8	2
multi-scale risk analysis	8	2
performance	8	2
renewable energy	8	2
structural rehabilitation	8	2
sustainability	8	3
urban landscape	8	2
urban sustainability	8	2
vulnerability	8	3
web-platform	8	2
economics	7	2
indicators	7	2
urban climate	7	2
urban policy	7	2
climate change adaptation	6	2
life cycle assessment	6	2
digital twin	5	3
gis	5	2
risk	5	3
urban planning	5	3
sdg	4	2
historic urban landscape	2	2

Fig. 7. Occurrence, link strength, and cluster for each keyword (source: Authors' elaboration).

governing cultural heritage frequently restrict invasive interventions [32], limiting technological options. Non-invasive and context-sensitive energy solutions are required to reduce energy consumption while preserving the cultural significance of historic cities [53]. In this respect, historic cities represent both a challenge and a strategic opportunity for sustainable urban development. The literature links UEM and SDGs, primarily through the digital transformation centred on digital twin technology [53,54]. It also underscores the potential of artificial intelligence in advancing sustainable urban development [55] and emphasizes the importance of public participation and awareness in achieving sustainability objectives [56].

Digital transformation contributes to environmental, economic, and social sustainability by enhancing the efficiency of public services and supporting climate mitigation efforts. In this context, urban sustainability is commonly framed through two related paradigms: smart cities and sustainable cities [57]. Smart cities employ advanced digital technologies, such as the Internet of Things (IoT), to enhance quality of life, operational efficiency, and sustainability [58]. By contrast, sustainable cities emphasize the responsible use of digital tools to manage resources and promote long-term environmental and social outcomes [59]. Digital transformation integrates technologies such as artificial intelligence (AI), big data analytics, cloud computing, IoT, social media, and mobile platforms to support sustainability across domains, including urban development, waste management, sustainable production, and pollution control [57,60]. This integration facilitates more efficient natural resources utilization in urban environments. Within this framework, digital twin (DT) technology has emerged as a core component for managing sustainable urban development. DTs enable the monitoring and projection of urban systems, reduce resource consumption such as land, water, and energy, and support continuous risk assessment to strengthen urban resilience [54]. A DT comprises three core components: the physical entity, the virtual model, and the data connections that link them. DT systems integrate hardware, software, and IoT infrastructures to enhance the accuracy and functionality of virtual representations [61]. A DT provides a comprehensive description of an actual or potential physical product, from the micro-level of atomic structure to the macro-level of geometric form [62]. The development of DT systems at the urban scale is supported by key technologies such as surveying and mapping, Building Information Modelling (BIM), IoT, 5G, collaborative computing, blockchain, and simulation. Digital twin cities operate through iterative learning and decision-making processes, analysing interactions among urban elements to improve governance in areas including energy, mobility, planning, and disaster response.

Surveying technologies, including infrared thermography (IRT) [35,63,64], UAVs [35,65,66], 3D laser scanning [35,67], and geographic information systems (GIS) [68,69], provide essential static data for urban analysis. BIM supports the urban assets and infrastructure management [53,70], while IoT and 5G networks enable real-time collection and feedback [71]. Blockchain facilitates secure transactions, logistics, and human activity [72,73]. Collaborative computing, supported by 5G, facilitates efficient and timely responses [65], and simulation tools support policy development, urban planning, and early warning systems [61]. In heritage contexts, DT technology enhances the management of historic urban systems. For instance, a three-axis DT framework at the urban scale, focusing on energy, mobility, and resilience, has been implemented in the historic city of Venice to support the sustainable urban governance [54]. This framework defines the core functions and key components of DTs in urban governance and aligns them with the SDGs. By structuring the system around three main axes, it simplifies implementation, reduces redundancy of platforms or tools, and limits the complexity of urban-scale DT systems. Beyond supporting sustainable development, DT technology also contributes to the preservation of historic cities and the promotion of cultural heritage [74]. Through the integration of IoT sensing and AI, it enables real-time monitoring, early warning, and data-informed emergency decision-making, thereby improving the efficiency and reliability of heritage protection. Moreover, virtual reality and human–computer interaction technologies enrich immersive experiences in urban planning and cultural exhibitions, promoting cultural transmission and encouraging greater public participation.

Climate change

Climate change affects cities through multiple pathways, including: (i) sea-level rise; (ii) intensified urban heat island (UHI) effects and heatwaves; (iii) increased frequency of extreme events (eg., droughts and floods); (iv) urban ecosystem degradation; (v) degradation or loss of cultural heritage; (vi) transformations of urban landscapes, and (vii) heightened public health risks from vector-borne diseases [4,5,75–78]. These impacts interact with existing natural threats, such as earthquakes and tsunamis, thereby amplifying overall urban vulnerability. In the literature, climate change in UEM is primarily examined through two key aspects: (i) macro-scale monitoring of UHI effects [24,75,79]; and (ii) local-scale assessments of microclimate and thermal comfort [80,81].

The UHI effect, which refers to elevated temperatures in urban areas compared to surrounding rural regions, is primarily driven by heat retention in buildings and surfaces. Contributing factors include complex urban topography, high building density, the replacement of permeable vegetated surfaces with impermeable materials, anthropogenic heat emissions, and reduced sky exposure, which limits nocturnal long-wave radiation exchange [82,83]. Ongoing urbanization and climate change are expected to intensify the UHIs, increasing energy demand, economic strain, and environmental degradation [84]. Historic cities are more vulnerable to natural disasters and climate change than modern cities due to the fragility of their architectural heritage and urban fabric [21,77]. This vulnerability depends not only on hazard intensity but also on the socioeconomic conditions of residents and the institutional capacity of local authorities to respond effectively [77,85]. The UHI effect increases overheating risk in historic centres, where microclimatic variations and thermal discomfort directly affect residents' health, living conditions, and heritage conservation.

UHI indicators, including land surface temperature (LST), normalized difference vegetation index (NDVI), and normalized difference built-up index (NDBI), quantify thermal conditions, vegetation cover, and built-up intensity [86]. These indicators collectively characterize thermal conditions and land-cover properties. These indicators improve the interpretation of UHI formation mechanisms and spatial distribution patterns. At finer spatial resolutions, localized assessments are particularly relevant in historic cities characterized by morphological heterogeneity. Composite indices, such as the Composite Heat Vulnerability Index (CHVI), illustrate an effective method for assessing climate vulnerability [79]. Geographic Information Systems (GIS) play a vital role by integrating multi-source spatial data and enabling quantitative analysis of environmental exposure, sensitivity, and adaptive capacity. In addition, GIS-based analyses of urban morphology, including porosity metrics and shading performance, support evaluations of energy efficiency and outdoor thermal comfort [80]. Wearable monitoring systems, functioning as mobile micro-weather stations, enable real-time environmental monitoring [81]. When combined with fixed weather stations, these systems allow for a more comprehensive, pedestrian-scale understanding of urban microclimates and support assessments of climate adaptability in both indoor and outdoor environments. In addition, remote sensing and UAV, characterized by extensive spatial coverage and multi-temporal observation capability, have become a core tool in UHI research [87]. Remote sensing is widely employed to identify heat-vulnerable areas, guide green space planning, and support mitigation strategies [88–90]. UAVs address limitations of conventional remote sensing, particularly in spatial and temporal resolution, by providing sub-metre resolution and flexible, on-demand observations of micro-scale dynamics [91,92]. Although constraints such as limited flight duration persist, improvements in endurance and cost efficiency may enable network-based UAV monitoring across multiple urban areas [93]. In addition, AI and data-driven methods have significantly enhanced UHI analysis [94]. Techniques including high-resolution downscaling, multi-source data integration, missing data reconstruction, and automated feature extraction improve the usability of remote sensing data [95–97]. Machine learning models enable accurate temperature prediction and thermal vulnerability assessment, while optimization algorithms support intelligent green space planning and mitigation strategy design [90]. These developments strengthen the capacity to analyse thermal dynamics across scales and enhance decision-making in urban climate management.

Despite their exposure to UHI effects, historic cities also present mitigation opportunities. Traditional passive design strategies provide superior thermal performance and higher levels of thermal comfort compared to modern urban environments [98]. These approaches enhance indoor comfort without relying on energy-intensive systems and utilize local resources efficiently [98,99]. Typical measures include reflective surfaces, compact openings, shading devices, high thermal mass materials, traditional roofs, vegetation, and courtyard configurations [24,100,101], widely observed across Mediterranean historic settlements [24,102]. At the urban scale, compact spatial configurations reduce solar exposure and enable mutual shading, while narrow street networks enhance microclimatic cooling and air circulation [24,98]. Traditional roofs promoting evaporative cooling further contribute to passive temperature regulation. When such buildings cluster together, they collectively mitigate UHI intensity and reduce energy demand [24]. Shading strategies in historic neighborhoods, including courtyard design and temporary structures, further enhance thermal comfort [103]. Green infrastructure provides an additional mitigation pathway. Vegetation reduces surface and ambient temperatures at both urban and building scales through parks, tree-lined streets, green roofs, and façades [104–106]. In historic districts, however, spatial constraints and conservation requirements often limit such interventions. The application of cool roofs, extensive green roofs, or permeable pavements is frequently restricted to preserve architectural integrity [107–109], while the prevalence of pitched roofs further constrains feasibility. Consequently, mitigation strategies in historic contexts must prioritize non-intrusive and reversible solutions that balance heritage conservation with enhanced climate resilience [108,110]. Effective measures must consider local characteristics, technical feasibility, and compatibility with cultural values to avoid compromising integrity and authenticity. For instance, studies in the historic center of Florence propose targeted greening of public spaces and deployable shading systems rather than large-scale structural modifications [108]. In Seville, localized interventions such as green walls, grass, and permeable surfaces have demonstrated cooling benefits in spatially constrained historic environments [110]. In addition, at the city scale, cooling strategies can also target buildings without heritage value. For such buildings, green façades and roofs can reduce radiant temperatures and improve pedestrian-level thermal comfort without compromising protected structures [111].

Circular economy

The circular economy (CE) is a production and consumption process that seeks to limit resource extraction and environmental impact by extending material lifecycles and reducing material and energy waste. It encourages shared use and service-based consumption while prioritizing renewable, non-toxic, and biodegradable materials with minimal lifecycle impacts [112]. In cities, CE strategies address pressures from population growth, urbanization, and climate change, including greenhouse gas emissions, water contamination, excessive waste generation, and inefficient energy use [113–115]. Within the literature, two main dimensions are commonly highlighted in examining the relationship between CE and UEM: i) the adaptive reuse of cultural heritage buildings (ARCH) in cities [116]; ii) the embodied energy of urban heritage.

Cities host a substantial stock of heritage buildings that contribute to socio-economic development, urban landscape formation, and identity strategies, while offering potential for sustainable development [116]. The value of heritage extends beyond individual structures to their surrounding environments, reflecting broader cultural and historical settings. Heritage conservation is inherently an economic process involving investment in cultural capital to sustain its ability to generate long-term cultural and economic benefits [117]. Beyond their heritage significance, heritage buildings incorporate functional systems, including heating, cooling, ventilation, lighting, cleaning, wastewater, and drainage systems, that are essential to overall performance [118]. When properly maintained, these systems can reduce energy demand, extend building lifespan, and enhance contributions to CE objectives [118,119]. Although CE and architectural conservation are defined differently, they converge in their shared objectives of preserving, restoring, and recreating value [120]. However, this alignment does not eliminate practical tensions, particularly when CE strategies involve substituting or introducing non-original materials. The conservation doctrine emphasizes the significance of authentic materials, whereas CE approaches may prioritise waste reduction through recycled components. Recent studies indicate these tensions can be mediated through criteria such as compatibility, reversibility, distinguishability, and minimal intervention, enabling CE interventions while safeguarding culturally significant fabric. The relationship between CE principles and heritage buildings becomes particularly evident in adaptive reuse practices (ARCH) [116]. Through retrofitting, rehabilitation, or redevelopment, buildings can be adapted to evolving community, environmental, and social needs while maintaining structural and cultural integrity [112]. Nevertheless, existing research suggests that many urban authorities have yet to fully recognize and exploit the synergies between CE strategies and ARCH [116]. Although heritage buildings are not confined to urban contexts, those with the highest adaptive reuse potential are predominantly located in cities, where they contribute to UEM. Integrating CE principles into heritage contexts is rarely straightforward. Such integration frequently conflicts with established conservation doctrines, particularly regarding material authenticity, structural integrity, and the introduction of non-original components. These conflicts cannot be resolved by simple substitution but rather through nuanced decision-making frameworks grounded in compatibility, reversibility, distinguishability, and minimal intervention, as established in international conservation practice [121]. Empirical evidence from adaptive reuse projects demonstrates that recycled or contemporary materials can be introduced without compromising heritage values when their use is limited to elements that preserve the legibility of the original fabric, such as reversible interior finishes, secondary structural supports, or visually distinguishable additions [122,123]. Authenticity does not depend solely on retaining all original materials; it also depends on maintaining the cultural significance and identity of the site, while accommodating functional and environmental improvements [124]. Reuse interventions remain consistent with conservation principles when guided by material compatibility and respect for original construction logic [125]. Although most documented cases operate at the building scale, the same assessment criteria—reversibility, legibility, and compatibility—also inform conservation planning and regulatory frameworks at the urban level, guiding decisions on the admissibility of recycled or non-original materials in historic districts [126]. Collectively, these findings suggest that circular practices can be aligned with conservation ethics when embedded within appropriate governance structures and when the historical and artistic significance of the urban fabric remains the primary reference for intervention design. However, reconciling these approaches is seldom straightforward. Interventions involving non-original or recycled materials often encounter practical and regulatory constraints regarding authenticity requirements and the preservation of character-defining features. Evidence from industrial heritage projects suggests successful integration depends on new components being reversible, visually distinct from the historic substrate, and materially compatible [122,123]. Similarly, studies on material recovery demonstrate that recycled components can be reintroduced without compromising cultural value when applied in areas of lower heritage sensitivity and when reversibility is ensured. Effective CE implementation depends not on avoiding trade-offs, but on managing them through transparent assessment frameworks that prioritise heritage significance while enabling sustainable material cycles.

Embodied energy refers to the total resources consumed during the building construction, including raw materials, energy inputs, and human labour [127]. In existing buildings, it represents a past investment embedded within the urban fabric and a valuable resource for sustainable transformation in cities [128]. Given that urban areas contain a substantial share of heritage buildings and traditional historic dwellings with high emissions but strong potential for low-carbon renovation, assessing their embodied energy is crucial [129,130]. As these structures often require restoration and maintenance, they provide opportunities to adopt materials with lower embodied energy. Understanding the embodied energy also supports informed decision-making and the development of strategies to reduce energy consumption over the building's lifecycle [131]. Improving the energy performance of historic urban areas requires enhancing thermal performance without compromising cultural integrity or increasing environmental degradation. Integrating local technologies with life cycle assessment (LCA) enables the identification of context-specific solutions with lower environmental impact [132]. LCA methods facilitate the evaluation and reduction of embodied energy, particularly during conservation and restoration phases. However, most studies focus on operational energy, with limited adoption of life cycle perspectives, especially at the urban level [52,133]. LCA approach highlights the need to improve operational efficiency while also preserving embodied energy through the retention and reuse of existing materials [134]. In addition, legislation addressing embodied energy and carbon emissions in heritage buildings remains underdeveloped, limiting progress toward life-cycle carbon reduction targets [52]. This gap is particularly critical for heritage contexts, where retrofit strategies must achieve whole-life carbon savings while safeguarding cultural value [133,135].

Energy efficiency

UEM increasingly requires sophisticated tools that reconcile energy efficiency with the complexities of dense, stratified, and often historically layered built environments. NDT techniques, when coupled with digital technologies such as BIM, GIS, remote sensing, and DTs, enable informed, scalable, and non-invasive diagnostics. Originally developed for small-scale structural assessments, NDT tools such as IRT, ground-penetrating radar (GPR), ultrasonic testing, and LiDAR are now central to broader strategies for evaluating energy performance, structural safety, and material degradation at neighbourhood and citywide levels [36,136,137]. The transition from building-scale to urban-scale diagnostics represents how cities understand and manage their energy performance, particularly in historic urban centres. This transition is grounded in two decades of theoretical and technological development. UAV-based infrared imaging represents a key innovation in urban-scale NDT. Combined with satellite datasets, it has been successfully matched with building archetypes and energy certifications datasets to generate accurate urban energy maps, as demonstrated in Cambridge [138]. Lin et al. achieved high-resolution district-scale thermal monitoring, collecting over 1.3 million thermal images in Singapore using FLIR A300 sensors [139]. Satellite-based land surface temperature further correlates with building-level energy use, supporting scalable energy performance assessment [140,141]. These approaches expand from local inspection to city-wide analysis, enabling the identification of thermal anomalies and UHI effects linked to urban form, materials, and land-use [142].

Digital technologies further enhance diagnostic capacity. [143]. Machine learning models have achieved high accuracy in land-use classification and energy estimation, while real-time data platforms support integrated analysis and training [144,145]. DTs provide a framework that integrates IoT sensoring, real-time monitoring, energy modelling, and predictive maintenance to facilitate cross-sector coordination of smart energy infrastructure (e.g., heating, cooling, electric grids) [146,147]. In historic urban contexts, DTs enable virtual representation and scenario-based evaluation of interventions. These systems integrate heterogeneous data streams and allow planners to simulate interventions virtually, bypassing physical implementation risks. Lombardi et al. demonstrate that advanced compression algorithms enable detailed modelling of entire historic centres while maintaining computational efficiency, thereby supporting collaborative planning among stakeholders [148]. Case studies in historic urban settings demonstrate these approaches. In Southern Italy, the GENESIS platform integrates seismic and energy diagnostics, enabling policymakers to access interventions that strengthen structural resilience and thermal comfort [149,150]. Web-based diagnostic platforms expand access to advanced modelling tools previously confined to specialised institutions and enable comprehensive evaluation of intervention priorities across historic districts. Cantagallo et al. and Cantagallo and Sangiorgio show how multi-scale open-source computational platforms process data to support decision-making that balances heritage preservation with sustainability goals [149,150]. These platforms allow planners to assess intervention impacts in historic centres, enabling evidence-based decisions and efficient resource allocation. In France, the THERMOCITY project combines satellite thermal imagery with ground surveys to produce detailed heat maps that comply with preservation requirements [151]. Participatory initiatives like "City 360" are pivotal in incorporating community knowledge into diagnostic data interpretation [152]. At the urban scale, satellite remote sensing enhanced by deep learning supports rapid and cost-effective identification of vulnerable heritage sites, while satellite data from Sentinel and PAZ enables cities to prioritise local inspections and integrate macro-level thermal insights with NDT-based diagnostics [153]. Advances in satellite sensing have further improved the detection of thermal anomalies in dense historic areas.

Recent diagnostic frameworks shift from building-based assessments to territorial-scale characterisation. By combining earth observation (EO), NDT, and heritage building information modelling (HBIM), researchers can identify district-level energy patterns through systematic analysis of surface temperatures, vegetation indices, and density metrics. Artopoulos et al. show that coastal and inland historic districts exhibit different thermal behaviours linked to morphology and environmental conditions [53], providing insights for neighbourhood-scale interventions. These approaches enable the identification of thermal hotspots and energy-inefficient zones across entire historic neighbourhoods, supporting district-wide energy planning. They also provide a basis for understanding how historic districts respond to environmental change and for developing predictive modelling of future energy performance. The integration of multiple NDT techniques proves particularly valuable in historic urban contexts. Tejedor et al. identified the need for holistic approaches combining photogrammetry, laser scanning, HBIM, IRT, and airtightness testing for heritage buildings [10]. The advantages of multi-sensor fusion are evident, as seen in projects in Vienna, where GPR and LiDAR were used together to map subsurface infrastructure in historic squares. Similarly, in Turkey, drone thermography complemented GPR for better heritage assessments [154].

Advances in urban diagnostics have also emerged from the need to operate within dense urban settings, with techniques like wavelet analysis and neural networks enhancing defect detection. Understanding these developments requires distinguishing building-scale from urban-scale diagnostics. Close-range methods such as IRT and photogrammetry detect small defects with high precision, whereas urban-scale approaches, such as satellite thermal imagery [151,153] and City 360 participatory platforms [152], focus on broader coverage, enabling vulnerability mapping and policy-oriented planning. Emerging multi-scale methods attempt to connect these perspectives. Combining drone data with satellite imagery produces layered thermal information that spans fine-grained features and city-wide patterns. Bridging these scales remains difficult because of mismatched resolutions and analytical methods, yet this integration is crucial for future resilient energy strategies in historic districts.

Although energy resilience is often described as achievable without affecting cultural value, empirical evidence suggests that it typically requires carefully managed trade-offs. Several adaptive reuse projects demonstrate that thermal and energy improvements may necessitate limited interventions on non-character-defining building components, provided that the architectural elements carrying primary heritage significance remain intact. For example, De Gregorio et al. and Coscia, Lazzari, and Rubino document cases in which reversible insulation layers, modular internal linings, and lightweight secondary structures were introduced to improve thermal performance while preserving the material authenticity and visual integrity of the historic envelope [122,123]. Gravagnuolo et al. suggest that conflicts between conservation requirements and sustainability targets can be mediated through participatory governance, multi-criteria evaluation, and a clear hierarchy of heritage values [155]. This demonstrates that effective interventions do not rely on eliminating compromise, but on structuring it through transparent, heritage-informed decision-making frameworks.

Nevertheless, transitioning to urban-scale diagnostics presents notable drawbacks. The detail of observations inevitably diminishes when shifting focus from individual buildings to broader urban areas. Fine-grained issues—such as small thermal bridges, moisture accumulation, and local envelope defects—are often obscured when they are aggregated across facades or blocks. This limitation is particularly critical in historic areas, where adjacent buildings may differ substantially in materials, construction phases, and exposure conditions. Additional challenges arise from integrating heterogeneous datasets within a unified analytical framework. Each source (satellite imagery, drone surveys, ground-based thermography, HBIM records) differs in scale, timing, and technical constraints. Standardizing these sources to fit urban models flattens the distinctive characteristics of many types of heritage risk. Although representative clustering streamlines urban analysis, it often overlooks irregular or hybrid conditions prevalent in historic fabrics. Moreover, uncertainties introduced by resolution difference, geolocation errors, and temporal misalignment can accumulate and distort energy simulations, especially in complex microclimatic contexts shaped by narrow streets, irregular layouts, and diverse materials. These limits do not diminish the value of urban-scale diagnostics but illustrate the importance of pairing broad analyses with targeted, site-level inspections. Many recent studies follow this approach: thermal mapping identifies potential "hot spots," after which teams use NDT tools on the ground to determine their causes. Combining scales typically produces more reliable insights in heritage contexts, where both general patterns and the specific conditions of each building must be considered. The multi-scale workflow clearly yields benefits: diagnostics become proactive, retrofit strategies integrate energy and heritage goals, and communities take on an active role. Nevertheless, significant challenges remain. Data interoperability across HBIM, GIS, and remote sensing systems is still limited [141,156], and the large data volumes generated by urban NDT surveys require substantial computational capacity. DTs further require rigorous calibration, transparent modelling approaches, and robust data governance to ensure reliability and acceptance [143,157]. Their application in urban energy also raises unresolved issues, including system latency, scalability, and cross-platform integration [157,158]. Furthermore, embedding these technological systems into institutional decision-making demands new forms of cross-departmental coordination and budget frameworks. Overall, these constraints make clear that urban-scale diagnostics must be interpreted with caution and consistently cross-validated through high-resolution in-situ investigations.

Renewable energy

RES originate from natural processes that are replenished faster than they are consumed. According to the UN, RES include six main categories: (i) solar energy, divided into photovoltaic and solar thermal systems; (ii) wind energy; (iii) geothermal energy; (iv) bioenergy, divided into biomass and biogas; (v) hydropower; and (vi) ocean energy [159]. Solar and wind energy have dominated the discussion on urban-scale RES integration in heritage areas thanks to the level of technological maturity, spatial flexibility, market readiness, and lower direct environmental impacts on ecosystems [160]. Solar systems enable distributed generation with minimal alterations to urban layouts [161], while wind energy can still be integrated through small vertical-axis turbines or peripheral installations [162,163]. Other RES require extensive subsurface drilling, large-scale water diversions, or marine infrastructure, often incompatible with heritage values. Geothermal systems are predominantly installed in new urban developments or *peri*-urban areas with minimal heritage constraints, as their main challenges include potential impacts on subsurface stability and conflicts with archaeological strata or foundational stability [164]. Bioenergy systems are mainly implemented in rural areas without any heritage values for both aesthetic considerations and emission regulations [165]. Hydropower is prevalent in rural or *peri*-urban areas with significant riverine resources, due to the potential impacts on aquatic ecosystems and urban waterways. Ocean energy is typically limited to coastal urban areas, where it demands robust infrastructural frameworks and long-term monitoring not easily compatible with coastal heritage landscapes [160].

In literature, the relationship between urban energy management and RES integration is articulated through two essential phases:

– Analysis of RES feasibility.
– Urban scale design.

RES feasibility involves the assessment of local resources, urban morphology, climatic conditions, and infrastructural constraints to determine the technical and economic viability of RES deployment. In heritage cities, it also requires the evaluation of RES impact in terms of material, visual, energy, and environmental compatibility. Material compatibility refers to the minimization of the physical and chemical impact on buildings and urban surfaces, following the principles of minimal intervention and material preservation. Material impact assessment involves the identification and definition of architectural values considering regulatory constraints and damage [166,167]. Visual compatibility focuses on the preservation of the original appearance of urban and architectural contexts in terms of colour, reflectance, texture, patterns, dimensions, features, and proportions. Visual impact assessment concerns the visibility of RES installations. Strategies have been widely developed, particularly for photovoltaic and wind energy technologies, mainly employing target-based approaches that incorporate visibility as a key parameter in optimization algorithms for potential integration [166,168–170], or matrix of criticity mapping of RES integration in heritage areas (e.g., LESO-QSV – Quality-Sensitivity-Visibility) [169,171]. Energy compatibility entails RES sizing according to the actual energy demands of the city, thereby ensuring their technical and economic efficiency. The evaluation of energy production focuses on the estimation of the potential of existing urban areas through the use of cadastral data and bottom-up modelling tools. Cadastral systems are web-based mapping platforms supported by mathematical models that determine solar or wind energy production capacity of building surfaces (e.g., roofs and façades) [172]. These tools are typically applied at both urban and landscape scales and are based on two-dimensional (2D) or orthophoto maps. They generally do not consider heritage constraints [24,25], mutual shading effects from aggregated buildings [173,174], or dimensions of vegetation and other urban elements [172]. Bottom-up models identify "*representative buildings*" through cluster analysis of statistical and technological data on building shapes, features, dimensions, materials, geometries, and orientations [175]. In these cases, the impact of urban morphology on RES potential is explicitly considered [172,174–184], through the integration of Geographic Information System (GIS) techniques and simulation tools (e.g., Climate-Based Daylight Modelling (CBDM), Radiance, Data-Interpolating Variation Analysis (DIVA), CitySim) [185–188]. These tools allow for advanced data management, cluster generation, query interactions, and digital mapping [177,189]. Several studies have also explored the influence of heritage values on cluster analysis, proposing estimation methodologies [190] and criteria for building type selection [173] in the assessment of solar potential within historic urban fabrics. Finally, environmental compatibility refers to the preservation of natural land and species that may be affected by RES installations. This aspect is particularly critical for wind technologies and offshore systems, where potential ecological impacts must be rigorously evaluated and mitigated [191–198].

RES design at the urban scale is principally illustrated through case study applications on large areas [199–201] and landscapes [202], as well as energy communities development [203,204]. In all these contexts, a recurring critical issue is the tendency to implement isolated, uncoordinated, and site-specific interventions that create benefit only in localized areas [202]. Conversely, the energy community model represents a collaborative framework in which residential, commercial, and public entities collectively generate, share, and consume RES. In heritage areas, this model is significant for boosting decentralized RES solutions while respecting the architectural and cultural value. A common strategy involves locating RES installations in less-restricted suburban or *peri*-urban zones and subsequently distributing the generated energy to historic city centres. This approach minimizes physical interventions within sensitive heritage contexts, extends RES benefits to populations that would otherwise be excluded due to stringent preservation regulations, reduces dependency on national energy grids, and significantly contributes to lowering overall carbon footprints.

Key findings

Overall, the findings indicate increasing convergence between urban sustainability and heritage conservation, albeit hindered by methodological and operational fragmentation that constrains systemic impact. Digitalisation emerges as a unifying thread across the reviewed domains: GIS-based frameworks, UAV-based thermal surveys, DTs, EO data, machine learning, and multi-scale data integration are consistently identified as key enablers for the sustainable management of historic cities and the assessment of climate and energy vulnerabilities. Nevertheless, their impact remains constrained by pilot-oriented applications, limited interoperability among heterogeneous datasets, and weak institutional coordination. The integration of circular practices and renewable energy integration strategies is reframing urban heritage preservation, repositioning historic fabrics as active components of city-wide material and energy cycles, where adaptive reuse, embodied energy conservation, and energy communities contribute to environmental transition. The central challenge is no longer purely technological, but structural and governance-related. In all domains, a significant gap persists between micro-scale studies and broader urban assessments, obstructing the translation of scientific evidence into robust policy and planning instruments. (Table 2).

Conclusion

This critical review has examined the current state of research on UEM in historic cities through an integrated approach combining bibliometrics, scientometrics, and thematic analyses. By analysing 371 publications spanning from 1998 to 2025, with particular focus on the 195 papers published during the rapid development phase (2020–2025), this study provides comprehensive insights into the evolution, current trends, and future directions of this emerging field, according to the research questions (RQ, Section 1). The key findings are synthesized across three dimensions:

1. *Research Evolution and Growth (RQ1):* The bibliometric analysis reveals a clear three-phase development trajectory: a slow exploratory phase (1998–2011), a stable development phase (2012–2019), and a rapid growth phase (2020-present). Notably, 53% of all studies were published between 2020 and 2025, signaling both increased academic attention and urgent practical needs in this field.
2. *Thematic landscape and integration (RQ2):* The scientometric analysis identified five interconnected research themes: Sustainable development, climate change, circular economy, energy efficiency, and renewable energy. These themes are not isolated but demonstrate significant cross-cluster integration, particularly through digital transformation technologies. The thematic analysis reveals several key findings:

– Digital transformation emerges as a unifying thread across clusters, with digital twins, IoT, and AI technologies enabling unprecedented integration of energy management with heritage preservation.
– Historic cities face significant heat-related risks, with the UHI effect manifesting at the macro scale, while thermal comfort and microclimate challenges at the local level directly impact residents' health, quality of life, and cultural heritage preservation.
– Heritage buildings, despite their preservation constraints, contain substantial embodied energy, and their adaptive reuse not only preserves heritage values but also extends building lifespans while reducing energy consumption and waste.
– Urban energy efficiency assessment is undergoing a paradigm shift, transitioning from single-building diagnostics to integrated, urban-

Table 2
Overview of clusters, main themes, predominant methods, key findings, and limitations(source: Authors' elaboration).

Clusters	Main themes	Predominant methods	Key findings	Limitations
Sustainable Development	Heritage-Driven Sustainability, Digitalisation, Governance	GIS Analysis,DTs	- Growing involvement of digital systems in historic cities - DTs supporting both sustainability and heritage conservation	• Fragmented adoption • Uneven data integration
Climate Change	UHI, Microclimate, Thermal Comfort, Vulnerability	UAV Thermal Surveys, EO, GIS Analysis	- Spatial heat vulnerability assessment using integrated data - GIS-based identification of heat-exposed heritage areas - UAV-based monitoring of urban thermal dynamics - Machine learning models for temperature prediction and vulnerability evaluation - Passive design strategy for climate adaptation in historic cities	• Limited linkages between micro- and macro-scale analyses • Non-intrusive constraints on mitigation strategies
Circular Economy	Adaptive Reuse, Embodied Energy, Material Cycles	LCA, ARCH	- Shared emphasis on value preservation in the circular economy and heritage conservation - Reuse strategies as a key mechanism in circular conservation - ARCH as a model for circular integration in heritage buildings	• Authenticity constraints • Limited legislation on embodied energy
Energy Efficiency	Urban-Scale Diagnostics, NDT, DTs	UAV-IRT, DTs, Remote Sensing, HBIM-NDT Fusion	- UAV and infrared imagery for urban-scale NDT - Machine learning for urban energy assessment - DTs for real-time urban diagnostics - Satellite remote sensing with deep learning for vulnerability detection - Integration of multiple NDT techniques for urban diagnostics - Thermal data fusion across UAV and satellite scales	• Reduced detail in urban-scale diagnostics • Data interoperability challenges • Coordination and budgeting constraints
Renewable Energy	RES Feasibility, PV Integration, RECs, Compatibility	GIS Solar Modelling, Visibility Analysis	- Compatibility constraints on RES feasibility - Energy community models reducing interventions and expanding shared RES benefits	• Visual and material constraints on adoption • Isolated site-specific interventions with limited scalability

Source: Authors' elaboration

scale system analysis through NDT techniques integrated with digital tools such as BIM, GIS, remote sensing, and digital twins.

- Solar and wind energy have emerged as the preferred renewable sources in historic urban areas due to their minimal infrastructure demands and compatibility with heritage constraints, whereas other sources (geothermal, bioenergy, hydropower, and ocean energy) face implementation barriers due to large-scale infrastructure requirements incompatible with heritage preservation.

3. Key Opportunities, risks and challenges (Q3): Opportunities for UEM concern:

- Digital technologies and platforms have revolutionized UEM in historic cities by enabling real-time monitoring and prediction of urban energy consumption, thermal comfort, microclimate, and cultural heritage conditions. This facilitates early risk warnings and data-driven emergency decision-making. The development of multi-scale diagnostic systems represents a breakthrough in energy efficiency assessments at the city level, particularly in the "*Energy Efficiency*" cluster (section 3.4).
- Traditional knowledge embedded in historic urban fabric offers valuable lessons for contemporary energy management. Vernacular design principles, including passive cooling strategies, narrow street configurations, and climate-adapted materials, demonstrate sustainable solutions that predate modern technology.
- Historic cities present a dual opportunity: buildings that lack insulation offer significant potential for energy efficiency improvements, while their traditional materials and climate-adaptive designs, such as ventilated roofs and narrow streets, support passive cooling and reduce energy consumption without compromising heritage values.
- The innovative renewable energy community model demonstrates how decentralized generation can overcome heritage constraints by locating installations in less-restricted areas while distributing benefits to historic centers, minimizing physical interventions, and expanding access for communities otherwise constrained by conservation regulations.
- Public participation emerges as a critical success factor in energy conservation within historic cities. Community-driven initiatives demonstrate that citizen engagement enhances awareness of both energy efficiency and heritage preservation while providing valuable local knowledge for intervention design.

However, this review reveals several critical challenges faced by UEM in historic cities:

- UEM in historic cities must navigate complex trade-offs between efficiency improvements and preservation of the material integrity, visual authenticity, and cultural value of heritage sites. Renewable energy integration requires not only technical and economic feasibility assessments but also rigorous compatibility analysis across material, visual, energy, and environmental dimensions.
- Current research and policy frameworks remain predominantly focused on operational energy while neglecting life cycle perspectives. This gap is particularly evident in the absence of legislation addressing embodied energy and carbon emissions in heritage contexts.
- While significant progress has been made in transitioning from building-scale to city-scale energy diagnostics, NDT techniques still face implementation barriers: limited data interoperability, lack of standardized protocols, insufficient transparency in AI models, and unresolved challenges in cross-platform integration.

It also identifies three critical pathways for advancing UEM in historic cities. First, research and policy should prioritize the transition from isolated pilot projects toward standardized, cross-platform infrastructures that enable systematic implementation at scale. Second, development must evolve from purely technical approaches to frameworks that integrate ethical considerations, institutional governance, and social equity. Third, planning paradigms must shift from top-down approaches to community-informed implementation that leverages local knowledge and ensures equitable benefit distribution. The emerging integration of AI, machine learning, and sensor networks with conservation principles offers unprecedented opportunities for creating truly sustainable historic cities.

Only through such systemic alignment, combining technological innovation with heritage values, community engagement with expert knowledge, and local interventions with city-wide strategies, can historic cities fulfill their potential as resilient, net-zero-ready environments that preserve cultural heritage while leading the energy transition. This transformation positions historic cities not as obstacles to sustainability but as laboratories for innovative solutions that harmonize past wisdom with future needs.

Future outlooks will analyze the integration of advanced NDTs into urban-scale energy management of historic cities. Improvement in resolution, portability, and data-integration capacity will facilitate more precise modelling of urban energy dynamics, support predictive maintenance strategies, and strengthen the capacity of cities to balance conservation requirements with the pressures of the energy transition. Future research should also examine how digital tools are adopted and governed in the Global South, where constraints in accessibility, cost, and data infrastructure may shape distinct implementation pathways.

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Declaration of competing interest

The authors declare they have no competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

Data availability

Data will be made available on request.

References

[1] U. Nations, '68% of the world population projected to live in urban areas by 2050, says UN', United Nations. [Online]. Available: https://www.un.org/uk/desa/68-world-population-projected-live-urban-areas-2050-says-un [accessed: Jul. 28, 2025].

[2] 'Cities - United Nations Sustainable Development Action 2015', United Nations Sustainable Development. [Online]. Available: https://www.un.org/sustainabledevelopment/cities/ [accessed: Jul. 12, 2025].

[3] Change C. Mitigating climate change. *Working Group III contribution to the sixth assessment report of the intergovernmental panel on climate change*, 2022.

[4] Carter JG, Cavan G, Connelly A, Guy S, Handley J, Kazmierczak A. Climate change and the city: building capacity for urban adaptation. Prog Plan Jan. 2015; 95:1–66. https://doi.org/10.1016/j.progress.2013.08.001.

[5] Gandini A, Garmendia L, San Mateos R. Towards sustainable historic cities: mitigation climate change risks. *Entrepreneursh Sust* 2017;4(3):319.

[6] 'Directive 2012/27/EU of the European Parliament and of the Council of 25 October 2012 on energy efficiency, amending Directives 2009/125/EC and 2010/30/EU and repealing Directives 2004/8/EC and 2006/32/EC Text with EEA relevance'. Accessed: Feb. 19, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2012/27/oj/eng.

[7] 'European Parliament. Directive (EU) 2018/844 of the European Parliament and of the Council of 30 May 2018 Amending Directive 2010/31/EU on the Energy Performance of Buildings and Directive 2012/27/EU on Energy Efficiency'.

Accessed: Feb. 19, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2018/844/oj/eng.

[8] 'Directive 2010/31/EU of the European Parliament and of the Council of 19 May 2010 on the energy performance of buildings (recast)'. Accessed: Feb. 19, 2025. [Online]. Available: https://eur-lex.europa.eu/eli/dir/2010/31/oj/eng.

[9] 'European Commission, A European Green Deal. Striving to be the first climate-neutral continent, (2019).' Accessed: Feb. 19, 2025. [Online]. Available: https://commission.europa.eu/strategy-and-policy/priorities-2019-2024/european-green-deal_en.

[10] Tejedor B, Lucchi E, Bienvenido-Huertas D, Nardi I. Non-destructive techniques (NDT) for the diagnosis of heritage buildings: traditional procedures and futures perspectives. Energ Build 2022;263:112029. https://doi.org/10.1016/j.enbuild.2022.112029.

[11] Huo T, Du Q, Xu L, Shi Q, Cong X, Cai W. Timetable and roadmap for achieving carbon peak and carbon neutrality of China's building sector. Energy 2023;274:127330. https://doi.org/10.1016/j.energy.2023.127330.

[12] Zhang X, Cheng X, Qi X, Yang K, Zhao Z. Evaluation of China's double-carbon energy policy based on the policy modeling consistency index. Util Policy 2024;90:101783. https://doi.org/10.1016/j.jup.2024.101783.

[13] 'Working Guidance for Carbon Dioxide Peaking and Carbon Neutrality in Full and Faithful Implementation of the New Development Philosophy-National Development and Reform Commission (NDRC) People's Republic of China'. Accessed: May 06, 2025. [Online]. Available: https://en.ndrc.gov.cn/policies/202110/t20211024_1300725.html.

[14] 'Action Plan for Carbon Dioxide Peaking befor 2030: National Development and Reform Commission (NDRC) People's Republic of China'. Accessed: May 06, 2025. [Online]. Available: https://en.ndrc.gov.cn/policies/202110/t20211027_1301020.html.

[15] 'China's Policies and Actions for Addressing Climate Change (2022)', Ministry of Ecology and Environment of the People's Republic of China. [Online]. Available: https://english.mee.gov.cn/Resources/Reports/reports/202211/P020221110605466439270.pdf.

[16] Allen C, et al. Modelling ambitious climate mitigation pathways for Australia's built environment. Sust Cities Soc 2022;77:103554. https://doi.org/10.1016/j.scs.2021.103554.

[17] 'DCCEEW. (2023b). Australia's emissions projections 2023.' [Online]. Available: https://www.dcceew.gov.au/climate-change/publications/australias-emissions-projections-2023.

[18] 'National Construction Code | NCC'. Accessed: May 07, 2025. [Online]. Available: https://ncc.abcb.gov.au/.

[19] 'Transforming our world: the 2030 Agenda for Sustainable Development | Department of Economic and Social Affairs'. Accessed: Jul. 12, 2025. [Online]. Available: https://sdgs.un.org/2030agenda.

[20] Nocca F. The role of cultural heritage in sustainable development: multidimensional indicators as decision-making tool. Sustainability 2017;9(10). https://doi.org/10.3390/su9101882. Art. no. 10.

[21] Lucchi E. Energy efficiency of historic buildings. Buildings 2022;12(2). https://doi.org/10.3390/buildings12020200. Art. no. 2.

[22] Aigwi IE, Duberia A, Nwadike AN. Adaptive reuse of existing buildings as a sustainable tool for climate change mitigation within the built environment. Sust Energy Technol Assess 2023;56:102945. https://doi.org/10.1016/j.seta.2022.102945.

[23] Mısırlısoy D, Günçe K. Adaptive reuse strategies for heritage buildings: a holistic approach. Sustain Cities Soc 2016;26:91–8. https://doi.org/10.1016/j.scs.2016.05.017.

[24] Cassar J, Galdies C, Azzopardi E. Sustainability of traditional, historical roofs in the mediterranean: a rediscovered opportunity for a carbon neutral future. Sustainability 2023;15(17):Sep. https://doi.org/10.3390/su151712723.

[25] Elena C, Fabio F. Energy resilience of historical urban districts: a state of art review towards a new approach. Energy Proc 2017;111:426–34.

[26] Panakaduwa C, Coates P, Munir M. Identifying sustainable retrofit challenges of historical Buildings: a systematic review. Energ Buildings Jun. 2024;313:114226. https://doi.org/10.1016/j.enbuild.2024.114226.

[27] Fouseki K, Cassar M. Energy efficiency in heritage buildings — future challenges and research needs. Hist Environ: Policy Prac Jul. 2014;5(2):95–100. https://doi.org/10.1179/1756750514Z.00000000058.

[28] McCaig I. *Retrofit in heritage buildings*. Understanding the Risks. 2017.

[29] Rispoli M, Organ S. The drivers and challenges of improving the energy efficiency performance of listed pre-1919 housing. Int J Build Pathol Adapt 2018;37(3):288–305. https://doi.org/10.1108/IJBPA-09-2017-0037.

[30] Piderit MB, Agurto S, Marín-Restrepo L. Reconciling energy and heritage: retrofit of heritage buildings in contexts of energy vulnerability. Sustainability 2019;11(3):823. https://doi.org/10.3390/su11030823.

[31] Lucchi E. Climate Mitigation and Adaptation Strategies for Cultural and Natural Heritage: From Conceptualization to Action. Amsterdam: Elsevier; 2025. https://doi.org/10.1016/C2024-0-01283-0.

[32] Mazzarella L. Energy retrofit of historic and existing buildings. The legislative and regulatory point of view. Energ Build 2015;95:23–31. https://doi.org/10.1016/j.enbuild.2014.10.073.

[33] Nair G, Verde L, Olofsson T. A review on technical challenges and possibilities on energy efficient retrofit measures in heritage buildings. Energies 2022;15(20):7472. https://doi.org/10.3390/en15207472.

[34] Thornbush M, Golubchikov O. Smart energy cities: the evolution of the city-energy-sustainability nexus. Environ Dev 2021;39:100626. https://doi.org/10.1016/j.envdev.2021.100626.

[35] Shariq MH, Hughes BR. Revolutionising building inspection techniques to meet large-scale energy demands: a review of the state-of-the-art. Renew Sustain Energy Rev 2020;130:109979. https://doi.org/10.1016/j.rser.2020.109979.

[36] El Masri Y, Rakha T. A scoping review of non-destructive testing (NDT) techniques in building performance diagnostic inspections. Constr Build Mater 2020;265:120542.

[37] Übelmesser L, Klingert S, Becker C. Comparing smart cities concepts. In: *2020 IEEE international conference on pervasive computing and communications workshops (PerCom Workshops)*; 2020. p. 1–6. https://doi.org/10.1109/PerComWorkshops48775.2020.9156219.

[38] A. D. Sánchez, M. de la Cruz Del Río Rama, and J. Á. García, 'Bibliometric analysis of publications on wine tourism in the databases Scopus and WoS', *European Research on Management and Business Economics*, vol. 23, no. 1, pp. 8–15, Jan. 2017, doi: 10.1016/j.iedeen.2016.02.001.

[39] Chadegani AA, et al. A comparison between two main academic literature collections. Web of science and scopus databases. 2013. *arXiv preprint arXiv:1305.0377*.

[40] Penning de Vries BBL, van Smeden M, Rosendaal FR, Groenwold RHH. Title, abstract, and keyword searching resulted in poor recovery of articles in systematic reviews of epidemiologic practice. J Clin Epidemiol May 2020;121:55–61. https://doi.org/10.1016/j.jclinepi.2020.01.009.

[41] Kara BC, Şahin A, Dirsehan T. BibexPy: Harmonizing the bibliometric symphony of Scopus and Web of Science. SoftwareX 2025;30:102098. https://doi.org/10.1016/j.softx.2025.102098.

[42] Echchakoui S. Why and how to merge Scopus and Web of Science during bibliometric analysis: the case of sales force literature from 1912 to 2019. J Market Anal 2020;8(3):165–84.

[43] R. Pranckutė, 'Web of Science (WoS) and Scopus: The Titans of Bibliographic Information in Today's Academic World', *Publications*, vol. 9, no. 1, Art. no. 1, Mar. 2021, doi: 10.3390/publications9010012.

[44] Van Eck NJ, Waltman L. Visualizing bibliometric networks. In: *Measuring scholarly impact:* methods and practice. Springer; 2014. p. 285–320.

[45] Su H-N, Lee P-C. Mapping knowledge structure by keyword co-occurrence: A first look at journal papers in Technology Foresight. Scientometrics 2010;85(1):65–79.

[46] Bortnyk S, Lavruk T, Peresadko V. Strategic spatial planning of territorial communities to achieve the sustainable development goals. VISNYK OF V N KARAZIN KHARKIV NATIONAL UNIVERSITY-SERIES GEOLOGY GEOGRAPHY ECOLOGY 2024;61:121–36. https://doi.org/10.26565/2410-7360-2024-61-10.

[47] L. Vilain, D. Laplume, I. De Smet, and C. Riviere, 'DEVELOPMENT OF A TOOL TO HELP THE REASONED DENSIFICATION OF VILLAGE CORES IN WALLONIA, BELGIUM', in *University of Mons*, J. Casares, Ed., 2022, pp. 199–209. doi: 10.2495/SDP220171.

[48] A. Aldegheishem, 'Assessing urban sustainability in Saudi Arabia: an empirical evidence from Al-Medina Al-Munawwarah', *ENVIRONMENTAL RESEARCH COMMUNICATIONS*, vol. 6, no. 5, May 2024, doi: 10.1088/2515-7620/ad352c.

[49] Grazuleviciute-Vileniske I, Seduikyte L, Daugelaite A, Rudokas K. Links between heritage building, historic urban landscape and sustainable development: systematic approach. Landscape Architect Art 2020;17(17):30–8. https://doi.org/10.22616/j.landarchart.2020.17.04.

[50] Lizundia I, Uranga EJ, Azcona L. A methodology to regulate transformation of a city's appearance due to energy efficiency building renovations: a case study: Errenteria (Spain). Heritage 2023;6(9). https://doi.org/10.3390/heritage6090321. Art. no. 9.

[51] Kalinauskas M, Mikša K, Inácio M, Gomes E, Pereira P. Mapping and assessment of landscape aesthetic quality in Lithuania. J Environ Manage 2021;286:112239.

[52] Lidelöw S, Örn T, Luciani A, Rizzo A. Energy-efficiency measures for heritage buildings: a literature review. Sust Cities Soc 2019;45:231–42. https://doi.org/10.1016/j.scs.2018.09.029.

[53] Artopoulos G, Fokaides P, Lysandrou V, Deligiorgi M, Sabatakos P, Agapiou A. Data-driven multi-scale study of historic urban environments by accessing earth observation and non-destructive testing information via an HBIM-supported platform. Int J Archit Heritage 2024;18(6):920–39. https://doi.org/10.1080/15583058.2023.2199408.

[54] Villani L, Gugliermetti L, Barucco M, Cinquepalmi F. A digital twin framework to improve urban sustainability and resiliency: the case study of venice. Land 2025;14(1). https://doi.org/10.3390/land14010083.

[55] Sepehri B, Almulhim AI, Adibhesami MA, Makaremi S, Ejazi F. Artificial intelligence role in promoting Saudi Arabia's smart cities: addressing SDGs for socio-cultural challenges. Социологическое обозрение 2024;23(4):20–47.

[56] Husar M, Ondrejicka V, Scacchi M. Involving citizens through walking: urban walks as a tool for awareness raising in historic built areas. In: *IOP conference series: materials science and engineering*, IOP Publishing, 2020, p. 022087.

[57] A. K. Feroz, H. Zo, and A. Chiravuri, 'Digital Transformation and Environmental Sustainability: A Review and Research Agenda', *Sustainability*, vol. 13, no. 3, Art. no. 3, Jan. 2021, doi: 10.3390/su13031530.

[58] Malik KR, Sam Y, Hussain M, Abuarqoub A. A methodology for real-time data sustainability in smart city: towards inferencing and analytics for big-data. Sust Cities Soc 2018;39:548–56. https://doi.org/10.1016/j.scs.2017.11.031.

[59] Bibri SE, Krogstie J. Smart sustainable cities of the future: an extensive interdisciplinary literature review. Sust Cities Soc 2017;31:183–212. https://doi.org/10.1016/j.scs.2017.02.016.

[60] Rosário AT, Dias JC. Sustainability and the digital transition: a literature review. Sustainability 2022;14(7). https://doi.org/10.3390/su14074072. Art. no. 7.

[61] T. Deng, K. Zhang, and Z.-J. (Max) Shen, 'A systematic review of a digital twin city: A new pattern of urban governance toward smart cities', *Journal of*

Management Science and Engineering, vol. 6, no. 2, pp. 125–134, Jun. 2021, doi: 10.1016/j.jmse.2021.03.003.

[62] Grieves M, Vickers J. Digital twin: mitigating unpredictable, undesirable emergent behavior in complex systems. In: *Transdisciplinary perspectives on complex systems: New findings and approaches*. Springer; 2016. p. 85–113.

[63] Tejedor B, Lucchi E, Nardi I. Application of qualitative and quantitative infrared thermography at urban level: potential and limitations. In: *New technologies in building and construction: towards sustainable development*; 2022. p. 3–19.

[64] Lucchi E. Applications of the infrared thermography in the energy audit of buildings: a review. Renew Sustain Energy Rev Feb. 2018;82:3077–90. https://doi.org/10.1016/j.rser.2017.10.031.

[65] Wang C, et al. Computing power in the sky: digital twin-assisted collaborative computing with multi-UAV networks. IEEE Trans Veh Technol 2025:1–16. https://doi.org/10.1109/TVT.2025.3559735.

[66] Zorbas D, Di Puglia Pugliese L, Razafindralambo T, Guerriero F. Optimal drone placement and cost-efficient target coverage. J Network Comput Appl 2016;75:16–31. https://doi.org/10.1016/j.jnca.2016.08.009.

[67] Hosamo HH, Hosamo MH. Digital twin technology for bridge maintenance using 3D laser scanning: a review. Adv Civ Eng 2022;2022(1):2194949. https://doi.org/10.1155/2022/2194949.

[68] Schrotter G, Hürzeler C. The digital twin of the city of zurich for urban planning. PFG 2020;88(1):99–112. https://doi.org/10.1007/s41064-020-00092-2.

[69] J. Park and B. Yang, GIS-enabled digital twin system for sustainable evaluation of carbon emissions: a case study of Jeonju City, South Korea. *Sustainability* 12(21) (2020), doi: 10.3390/su12219186.

[70] Radzi AR, Azmi NF, Kamaruzzaman SN, Rahman RA, Papadonikolaki E. Relationship between digital twin and building information modeling: a systematic review and future directions. Constr Innov 2024;24(3):811–29.

[71] Zhang Z, Wen F, Sun Z, Guo X, He T, Lee C. Artificial intelligence-enabled sensing technologies in the 5G/internet of things era: from virtual reality/augmented reality to the digital twin. Adv Intell Syst 2022;4(7):2100228.

[72] Suhail S, et al. Blockchain-based digital twins: research trends, issues, and future challenges. ACM Comput Surv (CSUR) 2022;54(11s):1–34.

[73] Yaqoob I, Salah K, Uddin M, Jayaraman R, Omar M, Imran M. Blockchain for digital twins: recent advances and future research challenges. IEEE Netw 2020;34(5):290–8.

[74] T. Yang, J. Li, M. Li, Y. Miu, Y. Tian, and L. G. Sun, 'The protection of the historical and cultural heritage of the ancient city of Suzhou An activated digital twin approach'.

[75] Brimblecombe P, Hayashi M, Futagami Y. Mapping climate change, natural hazards and Tokyo's built heritage. Atmosphere 2020;11(7). https://doi.org/10.3390/atmos11070680. Art. no. 7.

[76] V. Vlami, I. P. Kokkoris, I. Charalampopoulos, T. Doxiadis, C. Giannakopoulos, M. Lazoglou, A transect method for promoting landscape conservation in the climate change context: a case-study in Greece. *Sustainability* 15(17) (2023) Art. no. 17, doi: 10.3390/su151713266.

[77] A. G. Bigio, 'Historic cities and climate change', *Reconnecting the City: The Historic Urban Landscape Approach and the Future of Urban Heritage*, pp. 113–128, 2014.

[78] Kumar P. Climate change and cities: challenges ahead. Front Sust Cities 2021;3. https://doi.org/10.3389/frsc.2021.645613.

[79] Kumari MR, Kitchley JL. A framework to assess the contextual composite heat vulnerability index for a heritage city in India- a case study of Madurai. Sust Cities Soc 2024;101. https://doi.org/10.1016/j.scs.2023.105119.

[80] Diz-Mellado E, López-Cabeza V, Roa-Fernández J, Rivera-Gómez C, Galán-Marín C. Energy-saving and thermal comfort potential of vernacular urban block porosity shading. Sust Cities Soc 2023;89. https://doi.org/10.1016/j.scs.2022.104325.

[81] Pioppi B, Pigliautile I, Piselli C, Pisello A. Cultural heritage microclimate change: Human-centric approach to experimentally investigate intra-urban overheating and numerically assess foreseen future scenarios impact. Sci Total Environ 2020;703. https://doi.org/10.1016/j.scitotenv.2019.134448.

[82] Parker DE. Urban heat island effects on estimates of observed climate change. WIREs Clim Change 2010;1(1):123–33. https://doi.org/10.1002/wcc.21.

[83] Gartland LM. *Heat islands: understanding and mitigating heat in urban areas*. Routledge; 2012.

[84] Wilby RL. A review of climate change impacts on the built environment. Built Environ 2007;33(1):31–45.

[85] Giuliani F, De Paoli R, Di Miceli E. A risk-reduction framework for urban cultural heritage: a comparative study on Italian historic centres. J Cult Heritage Manag Sustain Develop Oct. 2021;11(4):499–515. https://doi.org/10.1108/JCHMSD-07-2020-0099.

[86] C. R. de Almeida, A. C. Teodoro, and A. Gonçalves, 'Study of the Urban Heat Island (UHI) Using Remote Sensing Data/Techniques: A Systematic Review', *Environments*, vol. 8, no. 10, Art. no. 10, Oct. 2021, doi: 10.3390/environments8100105.

[87] Stathopoulou M, Cartalis C. Daytime urban heat islands from Landsat ETM+ and Corine land cover data: An application to major cities in Greece. Sol Energy Mar. 2007;81(3):358–68. https://doi.org/10.1016/j.solener.2006.06.014.

[88] Bai H, Li Z, Guo H, Chen H, Luo P. Urban green space planning based on remote sensing and geographic information systems. Remote Sens (Basel) 2022;14(17):4213.

[89] X. Wu, Q. Liu, C. Huang, and H. Li, 'Mapping Heat-Health Vulnerability Based on Remote Sensing: A Case Study in Karachi', *Remote Sensing*, vol. 14, no. 7, Art. no. 7, Jan. 2022, doi: 10.3390/rs14071590.

[90] F. Li, T. Yigitcanlar, M. Nepal, K. N. Thanh, and F. Dur, 'A Novel Urban Heat Vulnerability Analysis: Integrating Machine Learning and Remote Sensing for Enhanced Insights', *Remote Sensing*, vol. 16, no. 16, Art. no. 16, Jan. 2024, doi: 10.3390/rs16163032.

[91] J. Naughton and W. McDonald, 'Evaluating the Variability of Urban Land Surface Temperatures Using Drone Observations', *Remote Sensing*, vol. 11, no. 14, Art. no. 14, Jan. 2019, doi: 10.3390/rs11141722.

[92] S. Dimitrov, M. Iliev, B. Borisova, L. Semerdzhieva, and S. Petrov, 'A Methodological Framework for High-Resolution Surface Urban Heat Island Mapping: Integration of UAS Remote Sensing, GIS, and the Local Climate Zoning Concept', *Remote Sensing*, vol. 16, no. 21, Art. no. 21, Jan. 2024, doi: 10.3390/rs16214007.

[93] Li S, et al. Effectiveness of potential strategies to mitigate surface urban heat island: a comprehensive investigation using high-resolution thermal observations from an unmanned aerial vehicle. Sust Cities Soc 2024;113:105716. https://doi.org/10.1016/j.scs.2024.105716.

[94] Zhao L, Fan X, Hong T. Urban heat island effect: remote sensing monitoring and assessment—methods, applications, and future directions. *Atmosphere* 2025; 16(7), Art. no. 7, doi: 10.3390/atmos16070791.

[95] Furuya MTG, et al. A machine learning approach for mapping surface urban heat island using environmental and socioeconomic variables: a case study in a medium-sized Brazilian city. Environ Earth Sci 2023;82(13):325. https://doi.org/10.1007/s12665-023-11017-8.

[96] Zhong X, et al. Downscaled high spatial resolution images from automated machine learning for assessment of urban structure effects on land surface temperatures. Build Environ 2024;264:111934.

[97] Zhang X, et al. Deep learning-based 500 m spatio-temporally continuous air temperature generation by fusing multi-source data. Remote Sens (Basel) 2022;14(15):3536.

[98] Salameh M, Touqan B. Traditional passive design solutions as a key factor for sustainable modern urban designs in the hot, arid climate of the United Arab Emirates. Buildings 2022;12(11):1811.

[99] Manzano-Agugliaro F, Montoya FG, Sabio-Ortega A, García-Cruz A. Review of bioclimatic architecture strategies for achieving thermal comfort. Renew Sust Energy Rev 2015;49:736–55. https://doi.org/10.1016/j.rser.2015.04.095.

[100] Tawayha FA, Braganca L, Mateus R. Contribution of the vernacular architecture to the sustainability: a comparative study between the contemporary areas and the old quarter of a Mediterranean city. Sustainability 2019;11(3):896.

[101] Fernandes J, Mateus R, Bragança L, Correia da Silva JJ. Portuguese vernacular architecture: the contribution of vernacular materials and design approaches for sustainable construction. Archit Sci Rev 2015;58(4):324–36.

[102] Matos AM, Delgado JM, Guimarães AS. Energy-efficiency passive strategies for mediterranean climate: an overview. Energies 2022;15(7):2572.

[103] Diz-Mellado E, López-Cabeza VP, Roa-Fernández J, Rivera-Gómez C, Galán-Marín C. Energy-saving and thermal comfort potential of vernacular urban block porosity shading. Sust Cities Soc 2023;89:104325.

[104] Moretti L, et al. Investigation of parking lot pavements to counteract urban heat islands. Sustainability 2022;14(12):7273.

[105] Atak M, Kara C, Asilsoy B, Özden Ö. The urban heat island in a coastal Mediterranean city: the case study of Kyrenia, Cyprus. Int J Adv Appl Sci 2019;6(8):1–8.

[106] Santamouris M. Cooling the cities–a review of reflective and green roof mitigation technologies to fight heat island and improve comfort in urban environments. Sol Energy 2014;103:682–703.

[107] Rosso F, et al. New cool concrete for building envelopes and urban paving: optics-energy and thermal assessment in dynamic conditions. Energ Build 2017;151:381–92.

[108] Ciacci C, Banti N, Di Naso V, Bazzocchi F. Evaluating UHI mitigation and outdoor comfort in a heritage context: a microclimate simulation study of Florence's historic center. Sustainability 2025;17(19):8760.

[109] Pisello AL, Cotana F, Nicolini A, Brinchi L. Development of clay tile coatings for steep-sloped cool roofs. Energies 2013;6(8):3637–53.

[110] Rezaie P, Lopez-Cabeza VP, Sola-Caraballo J, Galan-Marin C. Cooling heritage scenarios: transforming historic squares for thermal comfort. Buildings 2025;15(4):564.

[111] Ascione F, Iovane T, Manniti G, Mastellone M. Urban and building scale strategies to cool cities: the case of a coastal city in the Mediterranean climate. Energ Build 2025:115998.

[112] Foster G. Circular economy strategies for adaptive reuse of cultural heritage buildings to reduce environmental impacts. Resour Conserv Recycl 2020;152:104507. https://doi.org/10.1016/j.resconrec.2019.104507.

[113] Innella C, et al. Experimenting urban living lab methodology on circular economy co-design activities in some Italian urban territories. Front Sust Cities 2024;6. https://doi.org/10.3389/frsc.2024.1406834.

[114] Liu Q, Xie M, Mi G, Yuan X. Integrating circular economy policies in urban policy making: Strategies for green energy and environmental management to reinforce city image in China. J Environ Manage Feb. 2025;375:124128. https://doi.org/10.1016/j.jenvman.2025.124128.

[115] Möslinger M, Ulpiani G, Vetters N. Circular economy and waste management to empower a climate-neutral urban future. J Clean Prod Oct. 2023;421:138454. https://doi.org/10.1016/j.jclepro.2023.138454.

[116] Foster G, Saleh R. The adaptive reuse of cultural heritage in European circular city plans: a systematic review. Sustainability 2021;13(5). https://doi.org/10.3390/su13052889.

[117] Ost C. Revisiting heritage conservation in its social and economic background. In *LDE heritage conference on heritage and the sustainable development goals: Proceedings, edited by a. Pottgiesser Uta, Fatoric Sandra, Hein Carola, Erik de Maaker, and Pereira Roders*, 2021, pp. 282–289.

[118] Ankaralıgil B, Dişli G. Sustainable and traditional technologies in Kutahya historic houses and their contribution to circularity: the case of Lajos Kossuth house. *VITRUVIO – Int J Architect Technol Sust* 6(1), Art. no. 1, Jun. 2021, doi: 10.4995/vitruvio-ijats.2021.15452.

[119] Dişli G, Ankaralıgil B. Circular economy in the heritage conservation sector: an analysis of circularity degree in existing buildings. Sust Energy Technol Assess 2023;56:103126. https://doi.org/10.1016/j.seta.2023.103126.

[120] Huuhka S, Vestergaard I. Building conservation and the circular economy: a theoretical consideration. J Cultural Heritage Manage Sust Dev 2019;10(1):29–40. https://doi.org/10.1108/JCHMSD-06-2019-0081.

[121] Huuhka S, Vestergaard I. Building conservation and the circular economy: a theoretical consideration. J Cultural Heritage Manage Sust Dev 2020;10(1):29–40.

[122] Coscia C, Lazzari G, Rubino I. Industrial heritage, adaptive reuse and sustainable redevelopment scenarios: including local communities' multiple values in the decision-making process. In: *Science of valuations: natural structures, technological infrastructures, cultural superstructures*. Springer; 2024. p. 347–60.

[123] De Gregorio S, De Vita M, De Berardinis P, Palmero L, Risdonne A. Designing the sustainable adaptive reuse of industrial heritage to enhance the local context. Sustainability 2020;12(21):9059.

[124] Vafaie F, Remøy H, Gruis V. Adaptive reuse of heritage buildings; a systematic literature review of success factors. Habitat Int 2023;142:102926.

[125] Godina M, et al. Strategies for salvaging and repurposing timber elements from existing buildings in the UK. J Clean Prod 2025;489:144629.

[126] Foster G, Saleh R. The adaptive reuse of cultural heritage in European circular city plans: a systematic review. Sustainability 2021;13(5):2889.

[127] Gordon D, Vaughan R. The value added properties of local historical preservation districts. J Appl Bus Res 2012;28(2):277.

[128] Guidetti E, Ferrara M. Embodied energy in existing buildings as a tool for sustainable intervention on urban heritage. Sustain Cities Soc 2023;88:104284. https://doi.org/10.1016/j.scs.2022.104284.

[129] Foster G, Kreinin H. A review of environmental impact indicators of cultural heritage buildings: a circular economy perspective. Environ Res Lett 2020;15(4):043003. https://doi.org/10.1088/1748-9326/ab751e.

[130] Qian Y, Leng J, Wang H, Liu K. Evaluating carbon emissions from the operation of historic dwellings in cities based on an intelligent management platform. Sust Cities Soc 2024;100. https://doi.org/10.1016/j.scs.2023.105025.

[131] Al-Zrigat ZM. BIM framework to minimize embodied energy in heritage buildings: old downtown Amman case studies. Facilities Dec. 2024;43(1/2):149–71. https://doi.org/10.1108/F-07-2024-0101.

[132] Egusquiza A, et al. Co-creation of local eco-rehabilitation strategies for energy improvement of historic urban areas. Renew Sustain Energy Rev Jan. 2021;135:110332. https://doi.org/10.1016/j.rser.2020.110332.

[133] F. Wise, A. Moncaster, D. Jones, and E. Dewberry, 'Considering embodied energy and carbon in heritage buildings – a review', *IOP Conf. Ser.: Earth Environ. Sci.*, vol. 329, no. 1, p. 012002, Sep. 2019, doi: 10.1088/1755-1315/329/1/012002.

[134] Thormark C. A low energy building in a life cycle—its embodied energy, energy need for operation and recycling potential. Build Environ Apr. 2002;37(4):429–35. https://doi.org/10.1016/S0360-1323(01)00033-6.

[135] Baker H, Moncaster A, Remoy H, Wilkinson S. Retention not demolition: how heritage thinking can inform carbon reduction. J Archit Conserv Sep. 2021;27(3):176–94. https://doi.org/10.1080/13556207.2021.1948239.

[136] Willmann A, Katscher L, Leiser T, Voelker C. A comparison of bottom-up and top-down modelling approaches in urban energy simulation for the assessment of city district data models. In: *Building simulation 2019* IBPSA; 2019. p. 3303–10.

[137] Martin M, Chong A, Biljecki F, Miller C. Infrared thermography in the built environment: a multi-scale review. Renew Sust Energy Rev Sep. 2022;165:112540. https://doi.org/10.1016/j.rser.2022.112540.

[138] He Y, et al. Energy mapping of existing building stock in Cambridge using energy performance certificates and thermal infrared imagery. Environ Data Sci 2024;3:e44.

[139] Lin S, et al. District-scale surface temperatures generated from high-resolution longitudinal thermal infrared images. Sci Data 2023;10(1):859.

[140] Mullerova D, Williams M. Satellite monitoring of thermal performance in smart urban designs. Remote Sens (Basel) 2019;11(19):2244.

[141] Tooke TR, Coops NC. A review of remote sensing for urban energy system management and planning. Joint Urban Rem Sens Event 2013;2013:167–70.

[142] Rasul A, et al. A review on remote sensing of urban heat and cool islands. Land 2017;6(2):38.

[143] Rayavarapu A, Kanuru R. The future of asset integrity: NDT powered by virtual reality. *e-J Nondestruct Test* 30(06), Jun. 2025, doi: 10.58286/31317.

[144] Li Y, et al. A comparison of various bottom-up urban energy simulation methods using a case study in Hangzhou, China. Energies 2020;13(18):Sep. https://doi.org/10.3390/en13184781.

[145] Li Z, Chen B, Wu S, Su M, Chen JM, Xu B. Deep learning for urban land use category classification: a review and experimental assessment. Rem Sens Environ 2024;311:114290.

[146] Kumari N, Sharma A, Tran B, Chilamkurti N, Alahakoon D. A comprehensive review of digital twin technology for grid-connected microgrid systems: State of the art, potential and challenges faced. Energies 2023;16(14):5525.

[147] Torzoni M, Tezzele M, Mariani S, Manzoni A, Willcox KE. A digital twin framework for civil engineering structures. Comput Methods Appl Mech Eng 2024;418:116584.

[148] Lombardi PA, Richter M, Komarnicki P. Balancing preservation and progress: a digital platform for decarbonizing heritage city centers. In: *IEEE Int* Humanit. Technol. Conf., IHTC, Institute of Electrical and Electronics Engineers Inc.; 2024. https://doi.org/10.1109/IHTC61819.2024.10855146.

[149] Cantagallo C, Sangiorgio V. 'An IT Tool for Managing Seismic Risk and Energy Performance of the Building Stock in Southern Italy', in *International Conference of Ar. Tec.(Scientific Society of Architectural Engineering)*, Springer, 2024, pp. 103–114.

[150] Cantagallo C, et al. Genesis: a web-based platform for managing the seismic risk of historic centres of southern Italy. Rehabend 2024:2522–30.

[151] Space for Climate Observatory, 'THERMOCITY : Thermography of cities from space', Mar. 27, 2024, *GEO Knowledge Hub*. doi: 10.60566/CCKWB-HQR05.

[152] Guo Y, Zhang Z, Baykurt B, Lin Q. Novel issues for urban energy-saving management: Renewal of leftover space. Sust Energy Technol Assess Feb. 2023;55. https://doi.org/10.1016/j.seta.2022.102934.

[153] Rodríguez-Antuñano I, Sousa J, Bakon M, Ruiz-Armenteros A, Martínez-Sánchez J, Riveiro B. Empowering intermediate cities: cost-effective heritage preservation through satellite remote sensing and deep learning. Int J Remote Sens 2024;45(12):4046–74. https://doi.org/10.1080/01431161.2024.2358544.

[154] Merkle D, Frey C, Reiterer A. Fusion of ground penetrating radar and laser scanning for infrastructure mapping. J Appl Geodesy 2021;15(1):31–45.

[155] Gravagnuolo A, Angrisano M, Bosone M, Buglione F, De Toro P, Girard LF. Participatory evaluation of cultural heritage adaptive reuse interventions in the circular economy perspective: A case study of historic buildings in Salerno (Italy). J Urban Manage 2024;13(1):107–39.

[156] I. Jeddoub, G.-A. Nys, R. Hajji, and R. Billen, 'Data integration across urban digital twin lifecycle: a comprehensive review of current initiatives', *Annals of GIS*, pp. 1–20, 2024.

[157] Aghazadeh Ardebili A, Zappatore M, Ramadan AIHA, Longo A, Ficarella A. Digital Twins of smart energy systems: a systematic literature review on enablers, design, management and computational challenges. Energy Inform 2024;7(1):94.

[158] Liu W, Lv Y, Wang Q, Sun B, Han D. A systematic review of the digital twin technology in buildings, landscape and urban environment from 2018 to 2024. Buildings 2024;14(11):3475.

[159] U. Nations, 'What is renewable energy?', United Nations. Accessed: Jul. 08, 2025. [Online]. Available: https://www.un.org/en/climatechange/what-is-renewable-energy.

[160] Lucchi E. Renewable energies and architectural heritage: advanced solutions and future perspectives. Buildings 2023;13(3):631.

[161] Lucchi E, Adami J, Peluchetti A, Zambrano JCM. Photovoltaic potential estimation of natural and architectural sensitive land areas to balance heritage protection and energy production. Energ Build 2023;290:113107.

[162] Trung KN, Dinh CT, Chu Q. Aerodynamic analysis of tulip wind turbine using computational fluid dynamics. Presented at the domestic conference on aerospace engineering and mechatronics. Vietnam: Hanoi; 2023.

[163] Basack S, Podder S, Dutta S, Lucchi E. Performance analysis and numerical modeling of mechanical and electrical components in a rooftop vertical-axis wind turbine. Energies 2025;18(7):1–29.

[164] Massarotti N, et al. Innovative solutions to use ground-coupled heat pumps in historical buildings: a test case in the city of Napoli, Southern Italy. Energies 2021;14(2):296.

[165] Gyadi T, Bharti A, Basack S, Kumar P, Lucchi E. Influential factors in anaerobic digestion of rice-derived food waste and animal manure: a comprehensive review. Bioresour Technol 2024:131398.

[166] Lingfors D, Johansson T, Widén J, Broström T. Target-based visibility assessment on building envelopes: Applications to PV and cultural-heritage values. Energ Build 2019;204:109483.

[167] 'Planning and Heritage Consultancy, Heritage Impact Assessment, "Heumarkt Neu" construction project and de-velopment of the "Historic Centre of Vienna" World Heritage property'. Accessed: Jul. 08, 2025. [Online]. Available: https://www.michaelkloos.de/en/projects/heritage-impact-assessments/heumarkt-and-historic-centre-vienna/.

[168] Dessì V. Visibility assessment of the integration of technologies from RES in sensitive urban environments. proposal for a simplified graphical tool. In: EWT Eco Web Town III/2015-I/2016; 2016. p. 1–14.

[169] Florio P, Peronato G, Perera ATD, Di Blasi A, Poon KH, Kämpf JH. Designing and assessing solar energy neighborhoods from visual impact. Sustain Cities Soc 2021;71:102959.

[170] Bonomo P, De Berardinis P. PV integration in minor historical centers: proposal of guide-criteria in post-earthquake reconstruction planning. Energy Procedia 2014;48:1549–58.

[171] Lucchi E, Romano G, Altamura P, Baiani S. 'Criticity mapping and integration quantity evaluation of solar installations in Mediterranean heritage territories. In: *Sustainability in energy and buildings*. Springer; 2023. p. 367–78.

[172] Chatzipoulka C, Compagnon R, Nikolopoulou M. Urban geometry and solar availability on façades and ground of real urban forms: using London as a case study. Sol Energy 2016;138:53–66.

[173] A. Peluchetti, G. Guazzi, E. Lucchi, I. Dall'Orto, and C. P. López, 'Criteria for building types selection in preserved areas to pre-assess the Building Integrated Photovoltaics solar potential-The case study of Como land area', in *IOP Conference Series: Earth and Environmental Science*, IOP Publishing, 2021, p. 012003.

[174] Gassar AAA, Cha SH. Review of geographic information systems-based rooftop solar photovoltaic potential estimation approaches at urban scales. Appl Energy 2021;291:116817.

[175] Horváth M, Kassai-Szoó D, Csoknyai T. Solar energy potential of roofs on urban level based on building typology. Energ Build 2016;111:278–89.

[176] Groppi D, de Santoli L, Cumo F, Garcia DA. A GIS-based model to assess buildings energy consumption and usable solar energy potential in urban areas. Sust Cities Soc 2018;40:546–58.
[177] Peronato G, Rastogi P, Rey E, Andersen M. A toolkit for multi-scale mapping of the solar energy-generation potential of buildings in urban environments under uncertainty. Sol Energy 2018;173:861–74.
[178] Mohajeri N, Upadhyay G, Gudmundsson A, Assouline D, Kämpf J, Scartezzini J-L. Effects of urban compactness on solar energy potential. Renew Energy 2016;93:469–82.
[179] Lucchi E. *Solar energy technologies in cultural heritage*. Elsevier; 2024. https://doi.org/10.1016/C2023-0-01039-1.
[180] Vartholomaios A. The residential solar block envelope: a method for enabling the development of compact urban blocks with high passive solar potential. Energ Build 2015;99:303–12.
[181] Redweik P, Catita C, Brito M. Solar energy potential on roofs and facades in an urban landscape. Sol Energy 2013;97:332–41.
[182] Rodríguez LR, Nouvel R, Duminil E, Eicker U. Setting intelligent city tiling strategies for urban shading simulations. Sol Energy 2017;157:880–94.
[183] Stendardo N, Desthieux G, Abdennadher N, Gallinelli P. 'GPU-enabled shadow casting for solar potential estimation in large urban areas. Application to the solar cadaster of Greater Geneva. Appl Sci 2020;10(15):5361.
[184] Blaise R, Gilles D. Adapted strategy for large-scale assessment of solar potential on facades in urban areas focusing on the reflection component. Sol Energy Adv 2022;2:100030.
[185] 'ClimateStudio', Solemma. Accessed: Jul. 08, 2025. [Online]. Available: https://www.solemma.com/climatestudio.
[186] 'CitySim Software'. Accessed: Jul. 08, 2025. [Online]. Available: https://www.epfl.ch/labs/leso/transfer/software/citysim.
[187] 'archelios PRO - Solar PV Design Software', Trace Software. Accessed: Jul. 08, 2025. [Online]. Available: https://www.trace-software.com/en/our-solutions/solar-pv-design-software/.
[188] 'Grasshopper'. Accessed: Jul. 08, 2025. [Online]. Available: https://www.grasshopper3d.com/.
[189] Hubinský T, Hajtmanek R, Šeligová A, Legény J, Morgenstein P. 'Analysis of photovoltaic modules integration applicability based on geographic information three-dimensional model. In: *Solar energy technologies in cultural heritage*. Elsevier; 2024. p. 365–86. https://doi.org/10.1016/B978-0-443-23989-2.00013-6.
[190] Lucchi E. Renewable energy and 20th-century architecture: mixed-methods research through documentary investigation, case-based inquiry, and expert consultation. Energy Build 2025;353:116869. https://doi.org/10.1016/j.enbuild.2025.116869.
[191] Méndez MG, Weidt J. World Heritage and wind energy. Planning Protecting visual integrity in the context of the energy transition Inspiring practices from four European countries. PH: Boletín del Instituto Andaluz del Patrimonio Histórico 2022;30(107):382–3.
[192] Wieduwilt P, Wirth P. Cultural heritage and wind turbines – a method to reduce conflicts in landscape planning and management: studies in the german ore mountains. European Country 2018;10(4):652–72. https://doi.org/10.2478/euco-2018-0036.
[193] Islam MK, Hassan NMS, Rasul MG, Emami K, Chowdhury AA. Assessment of solar and wind energy potential in Far North Queensland, Australia. Energy Rep 2022; 8:557–64. https://doi.org/10.1016/j.egyr.2022.10.134.
[194] Caceoğlu E, Yildiz HK, Oğuz E, Huvaj N, Guerrero JM. Offshore wind power plant site selection using Analytical Hierarchy Process for Northwest Turkey. Ocean Eng 2022;252:111178.
[195] Díaz H, Loughney S, Wang J, Soares CG. Comparison of multicriteria analysis techniques for decision making on floating offshore wind farms site selection. Ocean Eng 2022;248:110751.
[196] Maxwell SM, et al. Potential impacts of floating wind turbine technology for marine species and habitats. J Environ Manage 2022;307:114577.
[197] Shadman M, Amiri MM, Silva C, Estefen SF, La Rovere E. Environmental impacts of offshore wind installation, operation and maintenance, and decommissioning activities: a case study of Brazil. Renew Sust Energy Rev 2021;144:110994.
[198] Doorga JRS, Hall JW, Eyre N. Geospatial multi-criteria analysis for identifying optimum wind and solar sites in Africa: towards effective power sector decarbonization. Renew Sustain Energy Rev Apr. 2022;158:112107. https://doi.org/10.1016/j.rser.2022.112107.
[199] Maccanti M, *et al.* Learning-by-doing methodology towards urban decarbonisation: an application in valletta (Malta), *Sustainability* 2023; 15(7). doi: 10.3390/su15075807.
[200] Hubinský T, Hajtmanek R, Šeligová A, Legény J, Špaček R. Potentials and limits of photovoltaic systems integration in historic urban structures: the case study of monument reserve in bratislava, slovakia. Sustainability 2023;15(3):2299.
[201] Lucchi E. Can photovoltaic retrofit redefine heritage value? Practical and theoretical evidence from meta-analysis and multi-criteria evaluation of 133 international case studies over 35 years. J Clean Prod 2026;563:148474. https://doi.org/10.1016/j.jclepro.2026.148474.
[202] Nicolini E. Energy Self-Sufficiency of Smaller Rural Centers: Experimental Approaches. Buildings 2024;14(6):1862.
[203] Tarpani E, et al. On renewable energy community implementation in historic cities: A city-scale validated model. Energy Build Jul. 2025;338. https://doi.org/10.1016/j.enbuild.2025.115709.
[204] Violano A, Merola M. Energy communities in smaller mediterranean urban centres. Sust Mediterr Constr 2021;2021(14):168–74.