smart cities

Review

Smart Cities and Urban Energy Planning: An Advanced Review of Promises and Challenges

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Abstract: This review explores the relationship between urban energy planning and smart city evolution, addressing three primary questions: How has research on smart cities and urban energy planning evolved in the past thirty years? What promises and hurdles do smart city initiatives introduce to urban energy planning? And why do some smart city projects surpass energy efficiency and emission reduction targets while others fall short? Based on a bibliometric analysis of 9320 papers published between January 1992 and May 2023, five dimensions were identified by researchers trying to address these three questions: (1) energy use at the building scale, (2) urban design and planning integration, (3) transportation and mobility, (4) grid modernization and smart grids, and (5) policy and regulatory frameworks. A comprehensive review of 193 papers discovered that previous research prioritized technological advancements in the first four dimensions. However, there was a notable gap in adequately addressing the inherent policy and regulatory challenges. This gap often led to smart city endeavors underperforming relative to their intended objectives. Overcoming the gap requires a better understanding of broader issues such as environmental impacts, social justice, resilience, safety and security, and the affordability of such initiatives.

Keywords: urban energy planning; smart city; advanced technologies; smart buildings; urban design and planning; transportation and mobility; smart grids; policy and regulatory frameworks

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1. Introduction

While cities cover a mere 3% of Earth's total land expanse [1], they are home to over half of the world's inhabitants [2] and play a crucial role as centers of energy consumption, with estimates showing that they annually consume 60% to 80% of the world's energy [3,4], mainly derived from non-renewable sources [5]. Moreover, from an environmental standpoint, cities bear significant responsibility for approximately 70% to 75% of global GHG emissions [4,6,7]. Projections suggest that by 2050, urban areas will cradle nearly 70% of the world's inhabitants [3,8]. Intriguingly, with every 1% increase in the urbanization rate, the consumption of non-renewable energy grows by about 0.72% [9]. This escalating urban population, coupled with heightened energy consumption and GHG emissions, although indicative of economic strides and societal advancement [10,11], simultaneously raises concerns about sustainability and resilience.

With energy as the lifeblood of modern cities, urbanization faces mounting pressures including escalating demands, environmental imperatives, diminishing non-renewable resources, fluctuating supplies and prices in global markets, infrastructural limitations, and the vulnerability of urban energy systems to the existential threat of climate change [12–14]. Furthermore, emerging research underscores the pivotal role of buildings, urban form and spatial structure, transportation systems, renewable energy (RE), energy infrastructure, and power grids in enhancing cities' energy profiles and performance [5,14–16]. By constructing and retrofitting energy-efficient systems, curbing urban sprawl, optimizing RE integration, improving urban microclimates, and fostering walkable and mixed-use urban settlements, cities can potentially break from a past built on energy-intensive sectors [13–15]. As such, the integration of energy planning into urban planning and management procedures is not just prudent but potentially transformative, especially when contextualized within the overarching goals of climate change mitigation and decarbonization [4,17,18].

The emergence of "Smart Cities" offers promising solutions to facilitate this integration and can address pressing energy and sustainability challenges through a new generation of information and data-driven urban and energy planning [14,19,20]. Grounded in the evolving field of urban planning and supported by technological advancements such as Artificial Intelligence (AI), Digital Twins (DTs), Remote Sensing (RS), Geographic Information System (GIS), Internet of Things (IoT), Intelligent Transportation System (ITS), and smart grids, smart cities aim to integrate Information and Communication Technologies (ICT) into city planning process [20–24]. These tools and technologies enable the optimization of energy consumption, the integration of RE sources into the urban fabric, a reduction in GHG emissions, and ultimately an improvement of the quality of urban life as a whole [19,25–27]. However, achieving the potential of the smart city model is not without hurdles along the way. The advancement of smart cities poses various challenges, including managing and interconnecting complex tools, platforms, and sensors, and gathering and analyzing large data sets while ensuring system interoperability and addressing security and privacy concerns [28–30]. Additionally, the rapid pace of technological change necessitates continuous adaptation and multidisciplinary cooperation among engineers, city planners, social and behavioral scientists, utility planners, and city administrators [31]. Ensuring equitable access to these smart solutions to prevent the emergence of "digital divides" within urban populations is another significant challenge [32]. Last but not least, financial constraints can also impede the large-scale deployment of advanced technologies from building to city scale [19,33,34].

While the existing literature highlights the transformative potentials and technological advancements associated with the energy aspects of smart cities, it does not thoroughly explore the complexities and challenges involved [30]. Specifically, this advanced review shows a dearth of scholarly investigations that assess the potential advantages and difficulties associated with energy-focused smart city initiatives. Addressing this deficiency is crucial and an advanced review in this domain can offer deeper insights into the multifaceted nature of smart city initiatives. Equipped with this knowledge, decision-makers and stakeholders can make more informed choices and policies, particularly concerning the inherent trade-offs elucidated by such studies. This review endeavors to bridge this gap by thoroughly examining the synergy between urbanization, energy planning, and smart city evolution, specifically addressing the following three questions:

- How has the research on the convergence of smart cities and urban energy planning transformed over the past three decades?
- What are the promising benefits and accompanying challenges that smart city initiatives introduce in the realm of urban energy planning?
- Why do some smart city projects, despite rapid technological advancements, struggle to consistently achieve energy efficiency and carbon emission reduction goals, while others succeed?

A methodology using bibliometric analysis and scoping review was employed to answer these questions. Initially, guided by the PRISMA Extension for Scoping Reviews (PRISMA-ScR) framework [35], we undertook a bifurcated literature selection procedure. The initial search of the literature yielded 9320 pertinent papers published between January

1992 and May 2023. We cataloged the metadata of these publications into VOSviewer software, generating co-occurrence maps of keywords. Several insights were gained from an in-depth examination of these maps. Firstly, this analysis identifies three distinct phases in the literature on smart cities and urban energy planning: an initial focus on technology, smart transportation, and sustainable urban governance (January 1992–2008), a middle phase emphasizing rapid technological advancements with a limited socioeconomic focus (2008–2017), and a recent trend towards integrating technological growth with socio-ecological and economic considerations (2018–May 2023). However, there is a notable gap between studies on the technical aspects of smart cities and those addressing their socio-economic and environmental. Secondly, the analysis unearthed five pivotal dimensions encapsulating the nexus between urban energy planning and smart city endeavors: 1. Energy use at the building scale, 2. Urban design and planning integration, 3. Transportation and mobility, 4. Grid modernization and smart grids, and 5. Policy and regulatory frameworks.

These dimensions served as the foundation for a second phase of review that involved scoping questions. Initially, subsequent scrutiny refined the obtained paper collection, narrowing it down to 193 key papers deemed suitable for an in-depth review and evaluation. This in-depth review revealed that the great majority of studies highlighted the advantages of incorporating energy systems into smart urban environments and there is a scarcity of research regarding the current and future challenges and obstacles that could undermine the effectiveness of nearly all energy-related smart city initiatives. Only in recent years has academia begun to scrutinize the prevailing and potential challenges. Furthermore, despite notable technological advancements and the myriad of smart city initiatives aiming to enhance urban energy efficiency across dimensions 1–4, a deficit in research exists regarding appropriate policy and regulatory frameworks.

The abovementioned identified issues could be among the main reasons why some smart city projects deviate from their energy and environmental objectives, exacerbate socio-economic disparities, and grapple with an array of technical challenges. Therefore, for smart city projects to truly augment urban energy sustainability, inclusivity, and resilience, there is an exigent need for integrative frameworks and policies. Such paradigms should transcend mere technical considerations, encompassing environmental and socio-economic determinants as well. To strike this balance, further research is needed on overall energy performance, environmental impacts, public engagement, socioeconomic justice and inclusion, technical and implementation complexities, and resilience, privacy, and security concerns of energy-related smart city initiatives.

2. Materials and Methods

In this advanced review, we employed an integrated bibliometric and scoping review methodology. As articulated by Page et al. [36], review papers play a significant role in compiling and analyzing existing knowledge in a particular field, allow for inquiry into questions unavailable to individual studies, identify shortcomings within primary research, and contribute to the development or evaluation of theories. In conducting this review, we followed the guidelines outlined in the PRISMA-ScR to ensure transparency and adherence to best practices [35]. Moreover, we performed this review utilizing the six stages suggested by Cooper and Hedges [37], which include problem identification, literature exploration, data evaluation, data analysis, interpretation of results, and presentation of findings.

We employed primary scientific sources from the Web of Science (WoS) database, the oldest and most widely used database of research publications and citations worldwide [38]. This approach was taken to avoid overlooking crucial and up-to-date sources, as well as to obtain reliable access to ontologies, underlying hypotheses, families of terms, main components, and processes. To direct the WoS literature search process, a preliminary review of 19 reports and documents, published by reputable organizations (Appendix B, Table A1), was conducted to extract an initial list of keywords for defining search strings. To ensure the relevance of the extracted keywords, a panel consisting of

14 experts from diverse fields such as urban planning, transportation planning, architecture, electronic engineering, computer science, geography, and energy and environmental policy was convened for consultation. Using a Delphi questionnaire, the experts rated the importance of each statement or keyword and submitted additional keywords not included in the initial questionnaire. This assessment utilized a Likert-type response scale consisting of five points ranging from "Extremely important" to "Not at all important". The administration of this survey was carried out through Google Forms in April 2023.

The next phase involved devising the research protocol and determining specific criteria for inclusion and exclusion (Table 1). These criteria play a crucial role in narrowing down the search scope and ensuring that only articles relevant to the topic are selected [35]. To create an effective search strategy, expert input was considered alongside these criteria, leading to the compilation of targeted search strings. Then, we reviewed and refined the search strings together to enhance accuracy and ensure consistent application of the inclusion and exclusion criteria. In each round, we screened the titles, abstracts, and keywords of the first 200 articles to further improve the search string's precision. After five rounds of development and refinement, the final search string yielded 11,800 papers. Using our predetermined inclusion and exclusion criteria, a total of 9320 papers were chosen to be imported into VOSviewer software (version 1.16.9) for bibliometric analysis.

Table 1. The inclusion and exclusion criteria.

Inclusion Criteria	Exclusion Criteria
Focus: papers that specifically address topics related to urban energy planning and smart cities	Out of Scope: papers that focus on specialized aspects or sectors such as technical and engineering papers
Relevance: papers that explore the relationship between various dimensions of urban energy planning and smart city initiatives	Irrelevance: papers focusing solely on urban energy planning dimensions or smart city initiatives
Time frame: papers published between January 1992 and 1 May 2023	Non-English language papers
Publication type: peer-reviewed journal articles and conference proceedings	Papers that are not peer-reviewed or lack scholarly rigor

It is worthwhile to note that during the preceding steps, we discovered that there have been remarkable advancements in smart city technologies, policy frameworks, and energy planning methods over the past three decades. The term "Smart City" emerged in the 1990s, bringing forth new possibilities for how modern technology could impact urban areas. Dameri and Cocchia [39] provided a comprehensive account of the origins of this concept, highlighting that its initial conceptualization occurred in 1992 by Gibson et al. [40] through their book titled "The Technopolis Phenomenon: Smart Cities, Fast Systems, Global Networks". Accordingly, we selected the time period from January 1992 to May 2023 to conduct this bibliometric and scoping review. Examining this period allowed us to gain a deeper comprehension of how urban energy planning practices have evolved and how smart city initiatives have been incorporated into rapidly changing energy landscapes.

VOSviewer is a freely accessible tool designed specifically for conducting bibliometric analyses. It utilizes the VOS mapping technique developed by Van Eck and Waltman [41], which stands for "visualization of similarities". One application of VOSviewer, serving as the foundation for this paper, is to generate visual maps depicting keyword relationships and networks using co-occurrence data [42]. By using this software, researchers can visually represent the connections and associations between keywords in a dataset, providing insights into their relationships, underlying co-occurrence patterns, and trends in specific research areas [43].

While bibliometric analysis can effectively handle and derive insights from the initial set of 9320 papers, we used a stringent filter to identify key papers for the in-depth review. The initial step involved applying the highly cited papers filter on the WoS, which trimmed the number of papers from 9320 to 254. Subsequently, we scanned these papers to identify those that cover one or more of the five identified dimensions and address potential advantages and/or challenges associated with integrating smart city initiatives into urban energy planning. This selection process culminated in a refined set of 193 papers. The total of 193 papers reviewed in this study exceeds the typical average number of review articles. Given the multidisciplinary and multifaceted nature of the investigated topic, it was imperative to encompass a broad range of literature to ensure all pertinent aspects were adequately addressed. The overall review process is illustrated in Figure 1.

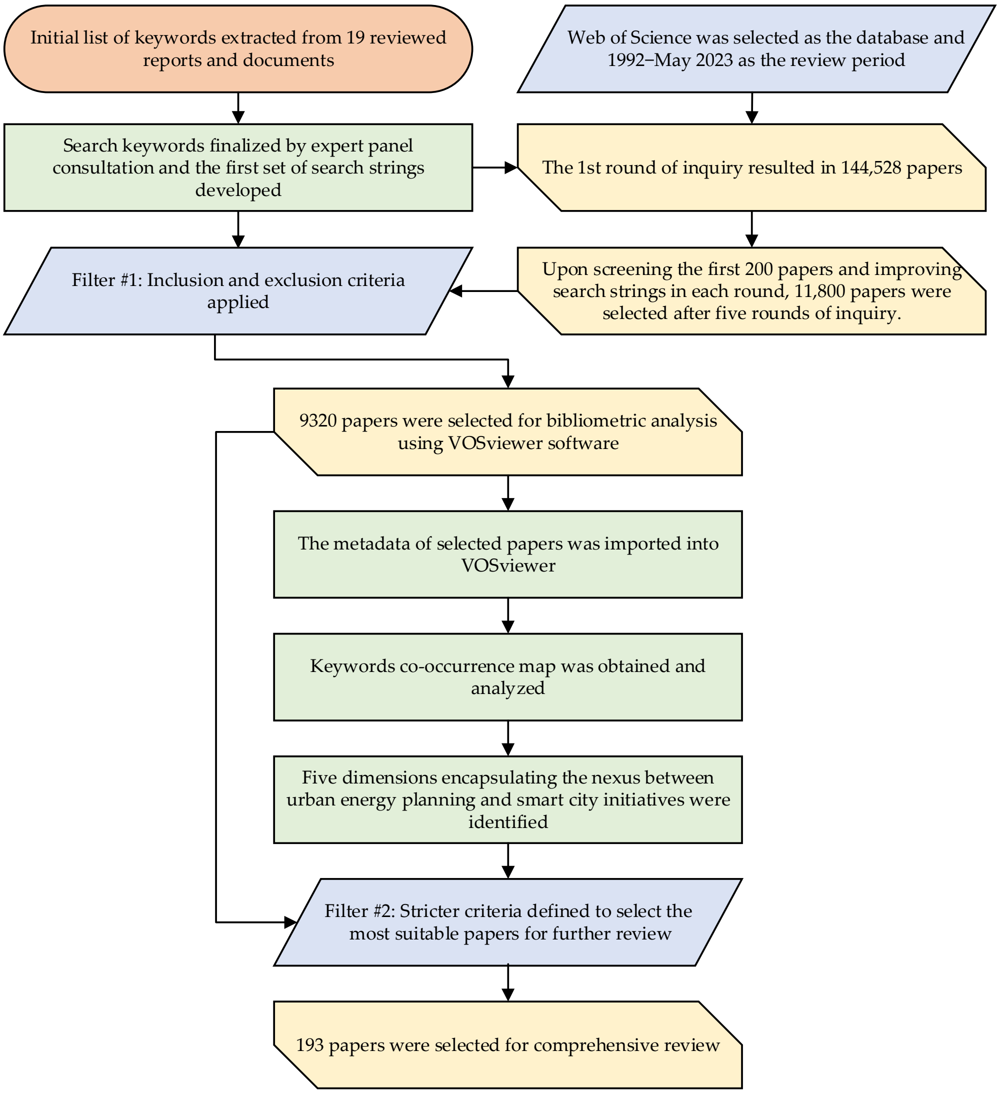

Figure 1. The review procedure.

3. Results of the Bibliometric Analysis

The co-occurrence map, crafted using VOSviewer software, illustrates a visual narrative of the research landscape, including keywords, clusters, and their interrelationships (Figure 2). Each node in this map represents a specific keyword, with the size of each node indicating its frequency or significance in the literature [42]. The connections between nodes represent frequent co-occurrences and suggest topics often discussed together. The thickness and proximity of these links indicate the degree of association between keywords. Nodes close to each other on the map tend to co-occur more frequently, reflecting a stronger relationship between them [43]. Additionally, there are three clusters whose keywords exhibit closer relationships with each other than with keywords from other clusters. Terms within the same cluster share thematic coherence, meaning they are often discussed in conjunction or in relation to each other.

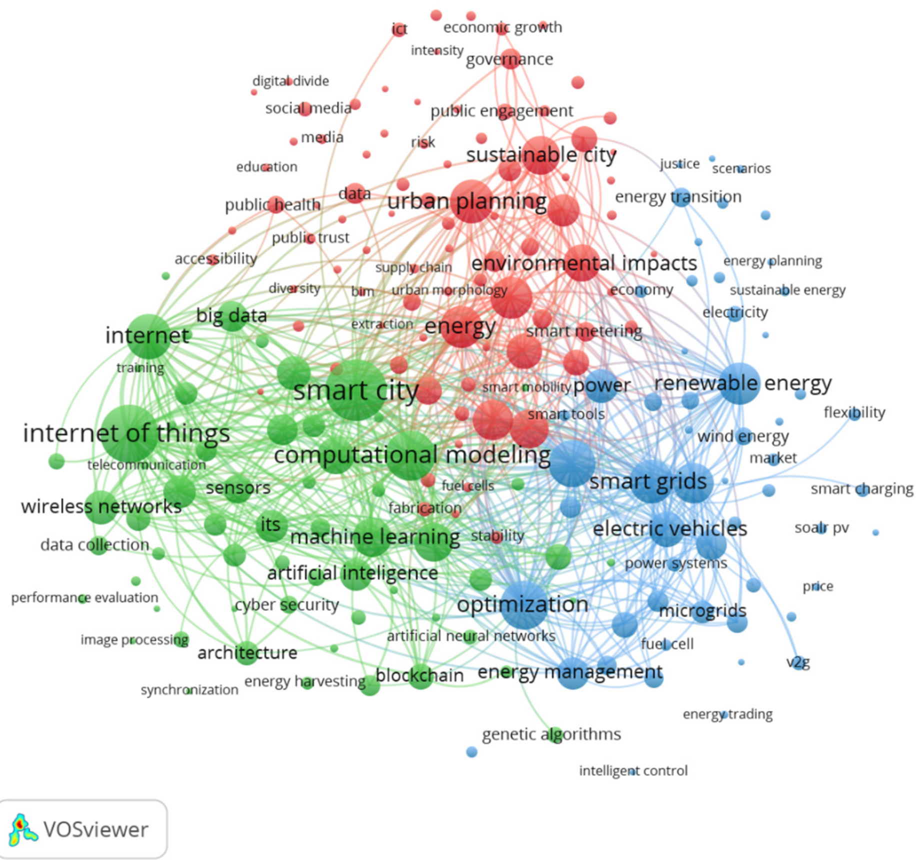

Figure 2. Keywords co-occurrence network (January 1992–May 2023).

In Figure 2, the first cluster, illustrated in green, draws attention to the significant role emerging technologies have in shaping urban energy systems. This cluster underscores the integration of AI, 5G, IoT, sensors, and other communication technologies, emphasizing their role in real-time data processing and decision-making. Notably, this cluster also accentuates concerns surrounding cybersecurity, privacy, and energy efficiency, highlighting the dual narrative of technological advancements and their potential challenges. The second cluster, in red, shifts the focus to the intersection of urban development and environmental sustainability, underscoring the need for sustainable practices amidst climate change discussions. However, this cluster reveals a disparity by incorporating technological advancements with human-centric issues. Lastly, the third cluster, colored in blue, portrays aspirations for a greener future, spotlighting the importance of energy transition and optimization and smart mobility solutions. This cluster delves into innovations such as Electric Vehicles (EVs) and their corresponding infrastructures, highlighting opportunities for city-wide transformation. Crucially, this cluster brings to the forefront the challenge of modern energy distribution the pivotal role of smart grids, and the nuances of balancing energy production, consumption, and trading in an ever-evolving urban environment.

The co-occurrence map reveals that the studies reviewed have addressed both positive prospects and concerns when it comes to integrating smart city tools and technologies into urban energy planning. However, positive and technocratic perspectives are prevalent rather than studies focused on addressing social concerns and obstacles. Critical social considerations, such as justice, public engagement, public trust, risks, public health, diversity, accessibility, and the digital divide are situated on the periphery of the network with smaller nodes and fewer connections to other nodes.

Figure 2 provides insights that confirm existing knowledge and open up new research directions. Some areas of the map show a high density of interconnected nodes, representing well-explored topics. However, there are other regions with relatively few connections, indicating areas that have not yet been extensively investigated. On the other hand, even within the highly connected clusters representing established fields of study, there may still be hidden gaps or unanswered questions that have gone unnoticed by mainstream academia.

Figure 3 shows that 77.5% of the 9320 scholarly papers were published between 2018 and May 2023. The concentration on research efforts within these years underscores the value of the comprehensive review conducted in the next section. Therefore, when considering the entire time span from January 1992 to May 2023, Figures 2 and 3 highlight both the significant development of the field and several prospects for further exploration.

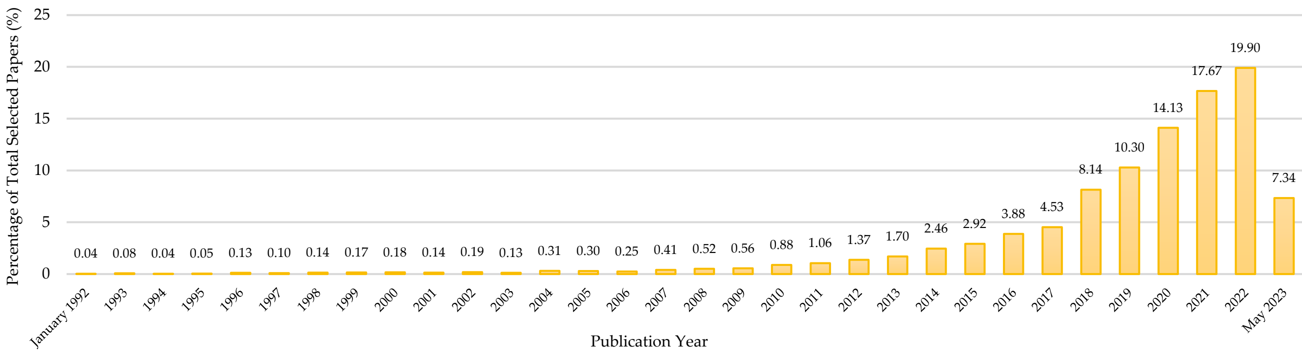

Figure 3. Annual distribution of 9320 selected papers by publication year.

Guided by the VOSviewer co-occurrence maps for each period, as illustrated in Figure 4, our bibliometric analysis emphasizes the progressive evolution of the literature on smart cities and urban energy planning through three transformative periods. The initial period from 1992 to 2008 was formative, merging technology with sustainability and governance, and giving rise to the role of smart transportation within urban energy and environmental planning. Between 2009 and 2017, rapid technological growth was accompanied by the emergence of AI, energy storage, smart grids, and EVs. However, socioeconomic factors were often overlooked. The most recent phase, 2018 to 2023, has sought to redress this by harmonizing technological growth with economic and socio-ecological priorities, influenced by the imperatives of climate change, energy transition, social and environmental justice, the COVID-19 pandemic, and privacy and security concerns and marked by widespread developments in 5G, DT, IoT, blockchain, big data analytics, and machine learning, among others. As Figure 4 shows, despite these advancements, a notable gap persists between the literature focusing on the technical dimensions of smart cities and studies addressing the socioeconomic and environmental implications, indicating the need for a more balanced research approach.

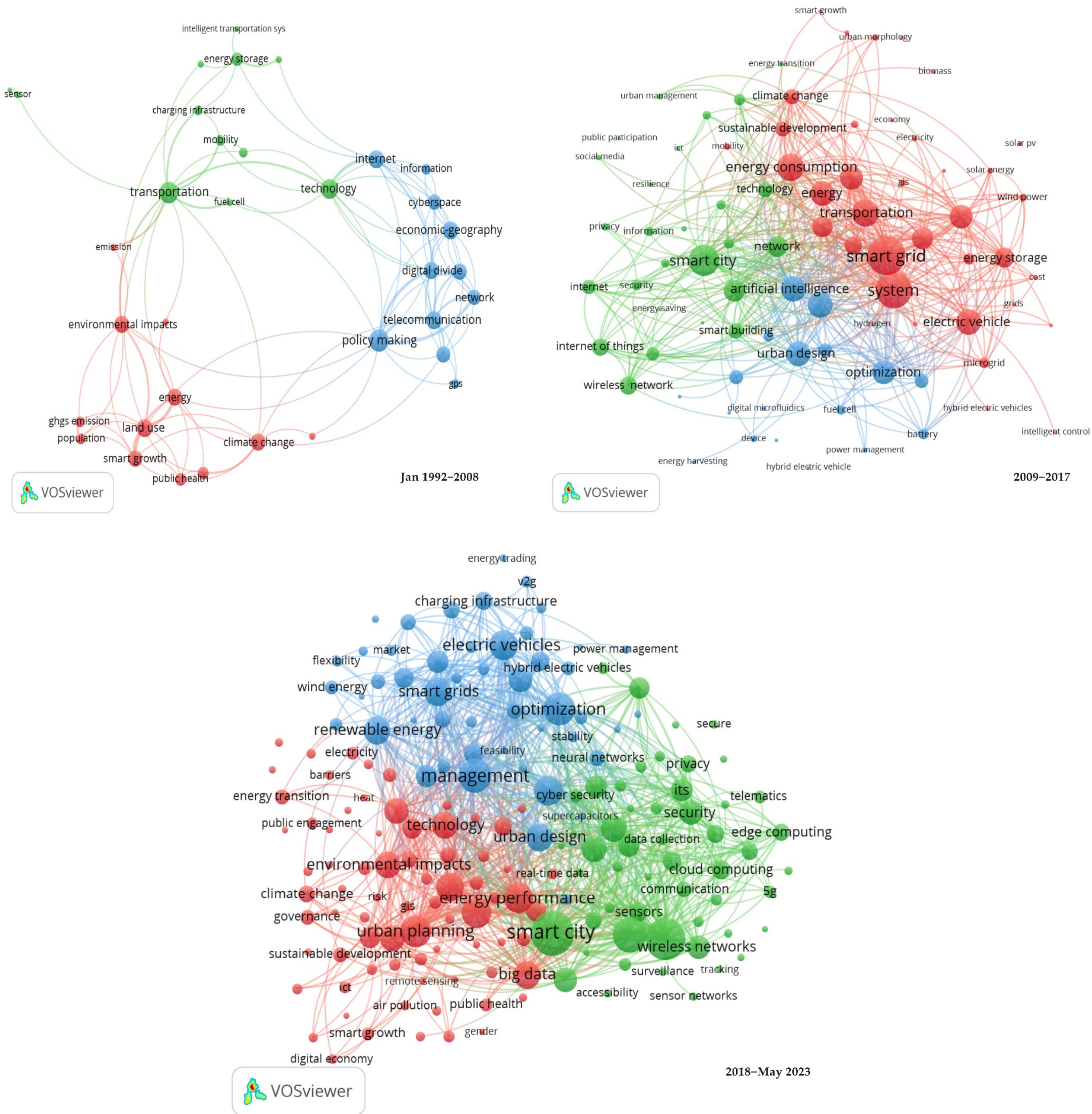

Figure 4. Evolving research trends in smart cities and urban energy planning: A three-period keywords co-occurrence analysis.

4. Navigating the Dual Landscape: Smart City Implications for Urban Energy Planning

Upon analyzing the keywords' relation within the co-occurrence map (Figure 4), five predominant dimensions were identified. These dimensions serve as the nexus between urban energy planning and smart city initiatives as demonstrated in the reviewed studies. Specifically, these dimensions encompass: "Energy use at the building scale", "Urban design and planning integration", "Transportation and mobility", "Grid modernization and smart grids", and "Policy and regulatory frameworks". The four technical dimensions were identified by observing the dense interconnections within and between clusters. These interconnections signify active areas of research in smart cities, highlighting the main thematic areas where technology intersects with urban energy planning. The fifth dimension, "Policy and regulatory frameworks", was discerned from smaller, peripheral nodes on the co-occurrence map that, despite their size, maintain connections to the keywords of the four technical dimensions, indicating its emerging significance and the need for further exploration in this area. In this section, we undertake a comprehensive review of selected papers to delve into these dimensions and specifically examine how smart city tools and technologies impact urban energy planning across the five identified areas.

4.1. Energy Use at the Building Scale

The literature on urban energy planning within the context of smart cities has primarily adopted a technocentric approach, emphasizing technological and algorithmic solutions for optimizing energy use in buildings, which account for approximately 40% of global energy consumption [16,44]. Smart buildings incorporate advanced technologies and systems alongside passive architectural design measures, aiming to enhance energy management [45–47]. Technologies such as DT [48], AI [45], and simulation software [4,48,49], when used during the design phase, consider factors such as geographical location and climate to propose optimal building design for energy efficiency [50]. During the operational phase, Demand-side Management (DSM) strategies [51], including energy-efficient technologies, smart metering and benchmarking [44,52], Smart Building Energy Management Systems (SBEMS), and demand response programs [45], use AI, Internet of Energy (IoE) and IoT devices to monitor occupant behavior and energy consumption patterns and make adjustments to energy systems [45,52–56].

Smart technologies and passive design also facilitate the integration of on-site RE generation [53,54], allowing buildings to adopt solar PVs and wind turbines efficiently [55,56]. However, the intermittency of these RE sources is an enduring challenge. AI techniques, using data from satellite imagery and meteorological stations, predict weather patterns to manage RE sources effectively [45]. Passive design optimizes the use of natural resources, reducing the reliance on traditional energy systems and promoting a reduction in overall energy demand [54,57,58]. Additionally, buildings equipped with smart technologies can connect to smart grids, acting as "Prosumers" (both producers and consumers) of energy [59]. They can utilize, store, or feed electricity into the grid, bolstering a resilient energy infrastructure and enabling smart grid systems to provide real-time data for more effective energy management [8,60,61]. Integrating smart technologies with passive design and RE sources thus holds the promise of transforming energy management in buildings, with significant implications for urban sustainability.

Smart city initiatives offer a promising vision for energy optimization in the building sector but also present significant challenges that warrant careful consideration [45,61,62]. High initial costs and questionable long-term profitability pose substantial barriers to the deployment of smart technologies, as the significant upfront investment required for smart systems and RE sources can deter adoption [33,34,63,64]. Within the 'Industry 4.0′ era, the rapid pace of technological change risks rendering these systems obsolete [64], resulting in scalability issues and the lack of interoperability among smart devices [63,65]. Integrating new technologies with existing building systems often necessitates costly upgrades or replacements, and maintaining these advanced systems requires ongoing management and specialized expertise [59,63,66]. Furthermore, the complexity of implementing passive design measures, which may be more demanding than traditional construction methods, leads to reluctance among some architects to adopt these energy-efficient practices [62].

The adoption of energy-efficient technologies in buildings faces resistance from stakeholders and is constrained by financial barriers [33,34,62]. Developers, contractors, and even end-users may be reluctant to embrace these technologies due to the upfront costs or a lack of perceived benefits [62,66]. Moreover, economically disadvantaged groups and even the average households may encounter difficulties when it comes to securing adequate funding to capitalize on these promising functionalities [34]. Additionally, practitioners within the building sector typically demonstrate limited proactive engagement in utilizing such energy-saving techniques [62]. These substantial infrastructure, capital, landlord and occupant engagement, and technical expertise required for the successful implementation of smart technologies compound the complexity and cost issue, representing a significant challenge in the transition to smart building practices.

Last but not least, smart technologies involve the collection and processing of large volumes of data, which gives rise to substantial concerns regarding privacy and security [61,63,65,67]. According to Farzaneh et al. [45], the primary obstacles lie in effectively managing, safeguarding, and examining data. In order to ensure the successful integration and acceptance of these technologies within our urban environments, it is crucial to implement protective measures that safeguard the vast amounts of data collected by smart buildings [65,67]. This plays a pivotal role in upholding public trust in these technological advancements [45].

4.2. Urban Design and Planning Integration

The success of smart cities is fundamentally anchored in technological advancement; however, this potential is amplified when synergistically integrated with intelligent urban planning and design [4,19,68,69]. It necessitates a unified approach where urban planning, design, energy management, and advanced technologies converge to optimize a network of interconnected smart buildings, thus catalyzing collective energy savings and extending the impact beyond the scope of individual buildings [18,70–72].

Like smart buildings, both active and passive measures are crucial in enhancing urban energy performance through urban design and planning [72]. Urban design significantly influences energy consumption, with the urban form and structure being key to reducing energy demands [15,73]. Integrating smart technologies and software into urban design enhances the effectiveness of these measures [49,74]. For example, the urban microclimate, influenced by the design and layout of spaces, affects energy demands for heating, cooling, and lighting [75]. Optimizing building orientation and spatial configuration using smart tools and RS technologies can regulate solar radiation and wind patterns, helping to control the urban microclimate [49,75,76]. GIS tools, Light Detection and Ranging (LIDAR), and 3D modeling can identify optimal sites for solar PV installations, assessing solar potential on rooftops [77–82]. RS and smart sensors are also vital in detecting and addressing the Urban Heat Island (UHI) effect, which exacerbates energy consumption and global warming [83,84]. Data collected informs interventions such as the placement of green spaces and the use of reflective or cooling materials to mitigate UHI effects [85]. Monitoring these interventions through RS technology creates a feedback loop for urban design, driving developments that minimize UHI impacts and optimize solar energy utilization [84].

Moreover, GIS and RS, combined with smart city technologies, bolster smart growth by aiding urban planners in promoting walkability and reducing reliance on energy-intensive transportation. They achieve this through strategic urban design that encourages compact city forms and enhanced land use, density, and zoning policies [15,86,87]. DTs and simulation software, leveraging data from mobile devices and IoT sensors, enable the modeling of commuting behaviors and energy consumption patterns, informing land use and transportation policies [88,89]. These tools also support the implementation of recent urban development concepts such as "15-min city", utilizing generative planning and technologies such as 6G and IoT to optimize the placement of amenities and improve city connectivity [90–92]. Additionally, the integration of GIS with Building Information Modeling (BIM) allows for the comparison of energy performance across urban development scenarios [3,4,93]. Furthermore, IoT-based energy management systems provide real-time insights into energy use [94], while machine learning systems can analyze data to forecast energy needs and enhance distribution in public spaces [95]. Smart meters and simulation monitoring systems furnish urban planners and utilities with immediate data on energy consumption, expediting the development of more effective energy management and conservation strategies [96,97].

Integrating smart initiatives into urban planning and design is pivotal for energy efficiency and urban growth, but several barriers could compromise their success. Key among these are the considerable infrastructure and investment demands necessary for the deployment of smart technologies. These technologies rely on robust digital, ICT infrastructure, and high-speed internet [98], often hindered by the digital divide affecting diverse socioeconomic areas, and the gap between developed and developing nations [99–101]. The significant capital required to introduce these technologies poses a formidable financial barrier, potentially beyond the reach of many cities [30,99]. Compounding this, the effectiveness of smart city services is dependent on access to extensive geospatial data, which can be restricted by the limited availability of necessary technology and data. Moreover, acquiring and analyzing large-scale geographical data, crucial due to smart city functions' reliance on geospatial data [81], faces hurdles in some areas, with access to essential large urban data sets such as LIDAR, GIS, and real-time information on traffic and energy usage often challenged by socioeconomic, political, and technical issues, including security, privacy concerns, and the varied technical requirements of smart technologies.

Urban planners and policymakers may encounter another notable challenge in the form of limited public engagement and acceptance [101,102]. These are particularly evident in smart city proposals that seek to modify city structures, such as changes in density and land use zones, or even renovating problematic urban areas aimed at optimizing the potential benefits of smart cities such as improving exposure to sunlight and natural ventilation or reducing buildings' operational and travel-related energy consumption. Such proposals often face conflicts with property rights held by citizens, making their implementation more difficult. For instance, many individuals may not be inclined to restructure their neighborhoods into mixed-used, walkable, densely populated neighborhoods like 15-min cities but instead prefer living in suburban areas where they can use their private vehicles rather than walking or utilizing public transportation [103]. Moreover, consider new smart city plans that propose redeveloping or repurposing urban areas. While these plans might promise better energy efficiency or functionality, the internationalism and one-size-fits-all approach behind these plans risks erasing a part of the city's culture and history, which once lost, cannot be reclaimed [104,105].

Furthermore, a significant challenge lies in ensuring equitable distribution of smart city risks and benefits [101,102]. Urban planners might be faced with decisions such as where to deploy smart infrastructure or how to ensure that technology-driven services (such as community solar power plants) are equally accessible to all residents not just affluent or technologically adept communities [101,106]. Therefore, if there is no/limited public acceptance and if the realization of the concept worsens the existing equity balance, research needs to be dedicated to overcoming these barriers. Moreover, with the proliferation of smart devices, from meters to household gadgets, solar PVs, and batteries, the quantity of Electronic Waste (E-waste) is expected to rise. E-waste often contains toxic substances that, if not disposed of properly, can harm the environment and human health. Therefore, urban planners and city officials face the challenge of finding appropriate sites for E-waste disposal and recycling, ensuring they are not situated near disadvantaged urban areas predominantly inhabited by low-income households [107].

4.3. Transportation and Mobility

Smart urban transportation, a cornerstone of smart cities, impacts various dimensions of urban living and significantly contributes to enhancing citizens' quality of life [108,109]. It is a crucial facet of smart cities, affecting not only transportation but also energy conservation, carbon footprint reduction, improved air quality, optimized land use, increased use of RE, social participation, and citizen safety [26,110]. ITS is instrumental in improving traffic management, reducing congestion, and shortening travel times [110]. Navigation, an early ITS function, helps urban residents find optimal routes through GPS, telematics, and IoT sensors, which provide real-time traffic data. These systems allow for dynamic routing and congestion avoidance using predictive algorithms such as neural networks and shortest-path calculations [111–113]. Furthermore, IoT-enabled smart parking systems guide drivers to available spaces, minimizing the time spent in search of parking and reducing congestion [114,115]. These smart mobility initiatives save commuting time and lower GHG emissions and energy consumption, underscoring their significant role in smart city evolution.

Moreover, the incorporation of advanced analytics, AI, and DTs into urban transportation planning is pivotal for creating energy-efficient and low-emission transport systems [116]. Urban mobility simulations and the Internet of Vehicles (IoV) are essential to recent DTs [117,118], using agent-based models to emulate urban movement patterns [119]. Large data sets from traffic sensors, smart meters, and mobile devices inform analyses of travel behaviors, allowing planners to simulate and evaluate the effects of various transport and land use changes [120]. This process aids in optimizing scenarios for energy use and GHG emissions reduction [121,122]. On a smaller scale, smart lighting systems in public spaces, powered by sensors, IoT devices, and energy-efficient LEDs, adjust brightness based on environmental and activity data, significantly cutting energy use and carbon emissions [106,123,124]. These systems also gather real-time data on mobility and energy usage, enabling dynamic traffic lighting management that can improve traffic flow and decrease fuel consumption and emissions by responding to the volume of vehicles, cyclists, and pedestrians [121–123]. Moving beyond driver-centric methods, future strategies will aim for collective optimization of traffic across networks, prioritizing overall flow [110].

Smart technologies such as IoT sensors, IoV, and GPS are revolutionizing urban mobility by optimizing public transit, micro-mobility, and shared transportation options [26,125]. Real-time tracking of buses and trains enhances commuting efficiency, diminishing the need for personal vehicle use [113,126]. Smart platforms improve carpooling and ride-sharing services by matching riders on similar routes, thereby easing traffic and lowering emissions [127,128]. Moreover, GIS and large data set analyses assist in determining optimal locations and capacities for bike-sharing and e-scooter stations, fostering the replacement of cars for short distances [128,129]. Additionally, multimodal transportation systems, underpinned by smart technologies, consolidate real-time traffic data to guide urban authorities in traffic management and provide travelers with the best transportation options for their needs, thereby reducing car reliance and promoting healthier, eco-friendly transport alternatives [113]. These efforts collectively aim at curtailing car dependency, alleviating congestion, enhancing physical activity, and championing sustainable transport networks.

Smart city initiatives are key to the broader adoption of EVs, Hybrid Electric Vehicles (HEVs) [130], and Connected and Autonomous Vehicles (CAVs) [131], offering significant benefits in reducing emissions and fossil fuel consumption [132]. Smart infrastructure supports this by establishing smart charging stations and Grid-to-Vehicle (G2V) facilities, providing convenient access for HEV and EV charging [130,133]. These stations, equipped with features such as RE sources, real-time pricing, and DSM strategies, promote off-peak charging to decrease grid load and energy costs [134,135]. Additionally, technologies such as wireless charging and Vehicle-to-Grid (V2G) systems enable EVs to supply excess energy back to the grid, effectively making them mobile energy storage units [130,131,133,136]. The integration of autonomous vehicles into smart city initiatives promises to revolutionize urban transport by optimizing routing and mitigating traffic, further aiding in energy and carbon footprint reduction efforts [124,131]. This holistic approach to vehicle electrification within smart cities is poised to play a transformative role in achieving sustainability targets.

Indeed, the transformation of transportation and mobility through smart city initiatives is a beacon of promise for enhancing energy efficiency and reducing carbon emissions. Nevertheless, bringing this vision to fruition is one of the smart city concept's most formidable challenges [109]. The integration of smart technologies into transportation, such as ITS, smart charging stations, and V2G technology, necessitates hefty capital investments, posing a substantial financial burden on cities [137]. The difficulty is compounded for cities with aging infrastructure, where the integration of new technologies isn't straightforward or cost-effective, particularly in older cities with established systems [138]. Adding to the financial concerns are technical hurdles and issues concerning communication, control, and security in implementing these advanced transportation systems [139]. As cities advance the use of EVs and other electric mobility options, a spike in energy demand looms, threatening to overburden electricity grids, risking outages, and grid failures, notably in regions with already stressed infrastructures or where EV adoption is rapidly climbing [140–143].

To manage the anticipated rise in energy demand from increased electric mobility, various solutions such as V2G, RE integration, and energy storage are proposed. However, each solution brings its technical and economic complexities [140,141,144]. V2G technology, for instance, demands secure bidirectional communication between EVs and the grid to prevent unauthorized access or control, which is crucial to safeguard against manipulation of charging cycles that could damage the grid and deplete vehicle battery life [135,144]. Moreover, as transport networks evolve to become more automated and IoT-based, they become increasingly susceptible to cyber-physical threats [145,146]. A single breach in such an interconnected system could have cascading effects, potentially disrupting traffic management systems and leading to road chaos, accidents, and injuries [147–150]. The resilience of smart transportation systems against such vulnerabilities remains a critical area for development to ensure the safe and efficient operation of future urban mobility networks.

In the complex domain of ITS, issues of privacy and security stand as significant challenges to their broader adoption. The core functionality of ITS relies on the transmission of vast amounts of data, which, if compromised through unauthorized access, poses a substantial threat. Such security breaches risk compromising user privacy by revealing sensitive travel data and could potentially allow for malicious tracking and personal information access [148,149]. This concern over the security of personal data managed by ITS is a notable factor in the hesitation to embrace these technologies. Additionally, the adoption of emerging transportation technologies such as CAVs encounters resistance due to safety, reliability, and the public's unfamiliarity with the technology [149]. Moreover, the shift towards EVs and multimodal transport systems is often met with skepticism. Despite the benefits of improved environmental impact and energy efficiency, the transition to EVs is gradual, hindered by issues such as range anxiety, the lack of sufficient charging infrastructure, and the economic burden of high initial investment and ongoing maintenance costs [132,151].

Following the ITS adoption barriers, it is crucial to recognize the social dimension where a digital divide in urban populations can further complicate matters. In cities worldwide, the digital divide manifests as a significant problem, with certain households and individuals becoming increasingly marginalized due to limited technological literacy or financial resources. This digital gap threatens to deepen social and environmental disparities by limiting access to smart transportation services, thereby risking a widening of inequality [152–154]. Moreover, the effectiveness of ITS is not solely determined by technological sophistication but also by how it aligns with user behavior. Urban planners must therefore consider the potential shifts in lifestyle, travel habits, and mobility patterns as smart technologies become more prevalent. Understanding these behavioral shifts is vital for accurately predicting their effects on energy consumption, carbon emissions, and urban air quality [155].

4.4. Grid Modernization and Smart Grids

The implementation of smart grids and the modernization of existing grid systems brings multifaceted benefits [156–158]. These enhancements are vital in reducing GHG emissions, enhancing energy security, optimizing smart city operation costs, and meeting the diverse and increasing energy demands of growing urban populations [157,159]. Smart grids integrate advanced data analytics [160], machine learning algorithms [161], DT technology [89], and IoE and IoT devices [162] to revolutionize energy distribution. This integration allows for precise monitoring and predictive control of consumption patterns, catering proactively to smart city infrastructural demands [161–163]. For example, IoT applications in smart grids facilitate the integration of diverse networks and technologies, enhancing the efficiency of energy management systems in smart buildings and cities [162,163]. Furthermore, multi-energy networks leverage IoT to unify the management of electricity, heat, gas, and traffic networks, ensuring a comprehensive energy strategy for urban areas [94]. This not only ensures efficient, reliable energy flow but also imbues the grid with the resilience to handle the variable nature of contemporary urban energy demands [164]. Beyond grid modification, there is a strategic shift towards reimagining energy systems, encompassing production, storage, and consumption. Energy storage, for instance, influences smart grid functionality by balancing supply and demand, storing surplus power during low demand, and deploying it during peak times, thus enhancing the grid's capability to manage energy efficiently [165,166].

Smart technologies, including blockchain, are vital for enhancing urban microgrids and decentralized energy systems, facilitating better coordination of distributed energy resources [167,168]. Microgrids provide a modular energy generation and distribution framework, leading smart cities towards a more resilient, multi-energy system away from traditional centralized models [167,169,170]. These multi-carrier microgrids, incorporating energy converters and storage alongside various energy sources such as electric, gas, heating, and cooling [169] bolster energy security and empower efficient operation of city infrastructures and transportation systems, particularly during grid disruptions [170,171]. Moreover, smart microgrids facilitate the cost-effective inclusion of RE sources, benefiting from the advanced management capabilities of modern technologies [170,172]. They efficiently handle the variability of RE and optimize grid performance, thereby increasing the share of renewables in smart city energy portfolios [158,169,172,173]. Nonetheless, the growing infusion of RE into grids presents the challenge of maintaining a balance between energy supply and demand [166,174]. The strategic deployment of energy storage within smart grids emerges as a solution, promoting efficient equilibrium and enhancing the reliability and efficacy of the energy system [165,174].

Section 4.3 highlights that the convergence of decentralized energy systems, such as smart grids, with advanced technologies such as V2G and EVs, brings additional advantages. V2G technology allows EVs to return electricity to the grid, offering demand response services that enhance grid functionality [134,139]. Decentralization, especially through blockchain-enabled smart grids, fosters local energy production [175–177] and empowers energy communities to engage in peer-to-peer (P2P) energy trading [176,178]. These communities benefit from automated, secure transactions facilitated by smart contracts, eliminating the need for intermediaries [176–179]. Such localized energy production, paired with demand response incentives, curtails transmission losses and bolsters grid balance, thereby heightening the efficiency and stability of the entire grid network [177]. Decentralization also ensures a more reliable integration of renewable energy sources into urban energy frameworks, improving their efficiency and reducing their carbon footprint [45,179,180]. This shift towards local energy autonomy not only increases citizen engagement in their energy consumption but also stimulates local economic growth. Ultimately, incorporating these innovative approaches within a decentralized energy model positions smart cities as leaders in sustainable urban energy planning, addressing local and wider societal, environmental, and economic goals [181].

Smart grids are heralded for their role in mitigating the energy crisis, reducing consumption, fostering flexible electricity markets, and enhancing consumer engagement [182]. However, they introduce challenges that can impact grid efficiency and security [183,184]. As Swain et al. [167] note, modern smart city solutions pose questions about energy efficiency and the security of data within smart grids, necessitating advanced expertise for effective management and safeguarding against cyber threats [183–185]. The complexities of protecting these grids require significant investments in technology and secure operational frameworks [183,186]. Additionally, the potential of energy storage technologies to stabilize smart grids is countered by the high costs and technical difficulties associated with large-scale implementation, hindering their widespread use [184]. The variability and unpredictability of RE sources further complicate their integration, despite advances in smart grids and data analytics [166,174,185,187]. Comprehensive solutions, including advanced technologies and robust cybersecurity measures, are imperative for effectively incorporating RE into smart grids [183,185].

Moreover, a significant challenge in the deployment of smart grids is the effective engagement of users and the enhancement of public awareness regarding these systems. [160,183,188]. There is currently a lack of customer demand for smart grid technologies due to limited incentives for consumers that regulate their electricity consumption [189]. Moreover, the broader goals of justice and inclusion should be at the forefront of these technological transitions. The decentralization of energy grids, while promising in its approach, necessitates a careful balance between innovation and equity [188]. Such systems hold the power to transform communities by providing them with autonomy over their energy sources and economic benefits, but this transformation must ensure that all citizens, irrespective of their socio-economic status, can reap those benefits. All residents, especially those in marginalized and economically disadvantaged communities, must have equitable access to the benefits of smart grid technologies [188,189]. Such issues, if overlooked, could further widen the socio-economic divide. In the context of local peer-to-peer (P2P) energy trading, it is crucial to address inherent trust and privacy concerns [183]. While decentralized systems integrated with blockchain technology may offer a solution to manage these concerns, high-performance computing, efficient data network management, and cloud-based computing methods are integral parts of these systems [50] and can elevate the overall cost and introduce additional complications [185]. Failing to address these challenges adequately will not only deter the holistic development of sustainable energy grids but also undermine the transformative potential of smart city initiatives, confining their benefits to a limited segment of the population.

4.5. Policy and Regulatory Frameworks

It is the task of policy and regulatory frameworks to support and accelerate the deployment of smart cities. To do so effectively, policy designs and regulatory platforms capable of overcoming the aforementioned challenges are needed. At the moment, ineffective, ill-conceived, or absent policies and regulations impede the successful implementation of smart city initiatives [190–192]. In particular, policymakers are faced with the imperative to position socioeconomic justice and inclusiveness as pillars of the smart city concept if the technical potential is to be achieved in a fair and just manner [32]. Without such a focus, those of us in society who are most exposed to socioeconomic, environmental, or other risks typically are left out when the benefits of technology implementation are distributed. For instance, although governments offer incentives for energy-saving technologies, the complexities of application and disbursement processes may deter adoption, particularly by low- and moderate-income households [62]. Moreover, certain smart city applications may inadvertently marginalize demographics such as the elderly, those less technologically adept, or residents living in disadvantaged urban areas [193,194]. Ignoring such circumstances can lead to project failure [195].

The policymaker and regulator have avenues available to pursue holistic designs and platforms that could help ensure fair benefit distributions, improve public trust, and make smart city service providers accountable to the public at large. One such design is to apply the wealth of data created by smart city technologies (IoT devices, sensors, smart meters, etc.) to the benefit of the community. For instance, high-resolution data on peak energy usage times across the city can inform DSM programs [196–198], enabling everyone in the community to lower their consumption at moments of peak cost [96] which especially benefits low-income customers who spend disproportionate amounts of their income on energy services. Empowering the community through the provision of real-time, granular data about energy consumption, grid performance, and user behavior in data-rich dashboards can significantly enhance public trust in energy policies and regulations [199]. By making energy data publicly accessible, smart city initiatives can enable citizens to better understand how energy is used in their city, how their own energy use compares to others, and how energy policies and regulations are impacting their community [199]. This transparency can foster a sense of ownership and engagement among citizens, encouraging them to participate more actively in energy conservation efforts and policy discussions.

Likewise, the data from smart city initiatives can provide a powerful tool for holding smart city service providers accountable. For example, integrating AI and IoT into energy systems can spark privacy and security concerns, necessitating clear policies on data access, protection, and liability [200,201]. Policies that outline guidelines and frameworks for tracking, measuring, and reporting energy use and grid performance, among others, can help to ensure that private sector companies and service providers are meeting their commitments and delivering on their promises [19]. This accountability can further build public trust, as well as drive improvements in energy management and policy-making [202]. In contrast, failure to elicit smart city service provider compliance with stated objectives may erode public trust as residents may perceive these initiatives as excessively intrusive or conclude that the drawbacks outweigh the benefits [191].

There is, in short, an essential need to continuously integrate smart city visions into the overarching city development goals to fully bring the promise of the smart city concept to life [203]. The rapid technological evolution of smart city components, which might result in temporary regulatory ambiguities or policy inefficiency, needs to be accompanied by a co-evolving policy and regulatory landscape that, through community engagement and participation, places community-wide development goals and objectives center-stage [204]. In this light, stakeholder engagement takes a central position in the development and implementation of policy frameworks as collaborative endeavors among city officials and residents improve policy effectiveness and integrate a wide spectrum of socioeconomic concerns, culminating in the adoption of smart city development strategies that are desired and to the benefit of the community at large [190].

5. Discussion and Conclusions

This conducted review showed that the energy performance of the building sector is transforming through the integration of technologies such as AI, DT, IoT, IoE, and RE sources in building design and construction [45,59,60]. These same technologies find application in urban planning and design, forming a synergy with passive measures to enhance energy efficiency. The deployment of IoT devices, remote sensing, GIS, and AI algorithms provides a unified approach, allowing for the optimization of RE harvesting, spatial planning, UHI mitigation, and energy demand prediction [50,82,85,94]. This emphasizes the interconnectedness of buildings and urban design and planning, showcasing the seamless integration of energy efficiency from individual buildings to the urban landscape. In the realm of smart transportation and mobility, technologies such as ITS, IoT-enabled solutions, V2G, and EVs represent a broader application of intelligent systems and technologies [106,123,124,145]. Grid modernization and smart grids mark the convergence of these initiatives. Enhanced with IoT devices and other smart technologies, smart grids increase control, predictive capabilities, and energy efficiency while fostering decentralized systems, energy storage, and RE integration [174,176,184,186,187].

These technological advancements are posited by some to be pivotal in empowering cities to predict, prepare for, and mitigate risks in real-time, turning reactive measures into proactive strategies, and fostering a resilient and sustainable future. Over the last three decades, a multitude of urban development concepts have emerged, inspired by the promising aspects of smart cities as illustrated in Figure 5. These initiatives are driven by the goal of transforming communities and urban areas into entities that are energy-efficient and carbon-neutral. This movement has given rise to an array of concepts and models, such as Smart Eco-City, Eco2 City, Ubiquitous Eco-City, Low Carbon City, Carbon Neutral City, Net Zero Carbon Community, Zero Carbon City, Low Energy District, Nearly Zero Energy Neighborhood, Zero Energy Community, Positive Energy Blocks, and ultimately, Positive Energy Districts (PEDs) [205,206]. Underpinned by these models, numerous smart city-based projects have been implemented or are in the planning stages globally. A notable example is the European Commission's objective to have 100 PEDs either planned, developed, or established by 2025 [207]. In the context of these varied and ambitious initiatives, a critical question arises: Why do some smart city projects, despite rapid technological advancements, struggle to consistently achieve energy efficiency and carbon emission reduction goals [105], while others succeed [206]?

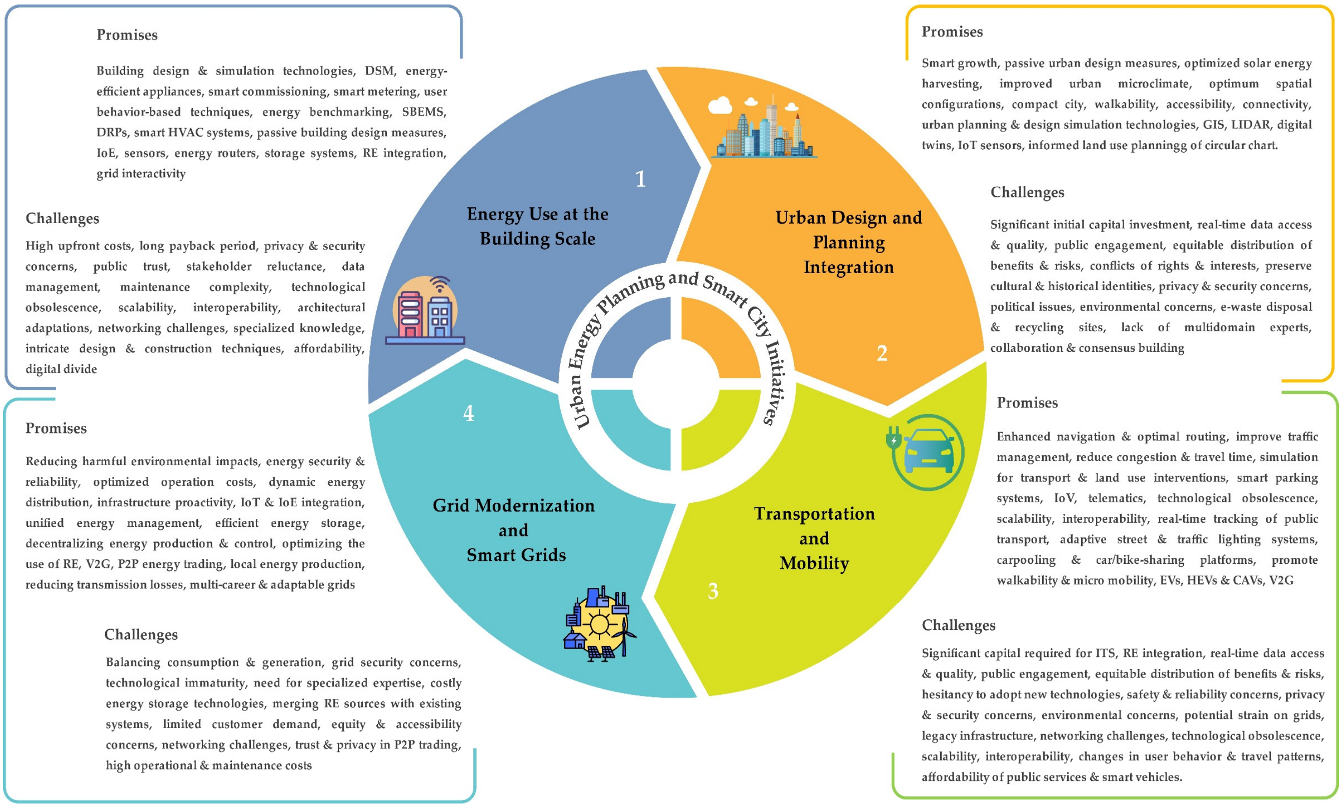

Figure 5. Mapping urban energy to smart city: An overview of promises and challenges.

Prior to addressing the aforementioned question, it is instructive to examine the definition of PEDs as outlined in the European "SET Plan Action 3.2 Smart Cities and Communities Implementation Plan [208]." PEDs encompass the integration of electric vehicles, advanced materials, local RE sources, local storage, smart energy grids, demand response, user interaction and involvement, ICT, and participatory energy management strategies in order to showcase a future where cities not only consume energy but also generate, store, and sustainably manage it [208]. In fact, the emergence of PEDs and other smart city-based concepts unfolds as a multidimensional transformation that not only emphasizes the technical and technological aspects but also implementation, performance evaluation, and management policies [105,205]. While there are multiple factors contributing to the varying success of smart city projects, one potential answer to the third question of this paper is the possible oversight of well-developed policies and regulations, which is a principal contributor to the challenges illustrated in Figure 5. Although some of these challenges are technical and technological in nature, more than half span across four dimensions and are directly linked to the absence of rigorous policies and regulations. These cross-cutting issues are pervasive, highlighting the imperative for a holistic and coordinated framework that addresses not only technical solutions but also policy and regulatory strategies.

If we conceptualize the four technical dimensions as the foundational infrastructure of the smart city and urban energy planning nexus, smart grids can be thought of as the central nervous system, interconnecting and coordinating these dimensions [209]. On the other hand, policy and regulatory frameworks act as the decision-making algorithms or central processing units that guide the operations. Without these guiding mechanisms, the system risks operational inefficiency, misalignment of goals, and potential failure in achieving smart cities' energy and emission reduction objectives [204]. Referring to the conceptual framework presented in Figure 6, enhancing physical infrastructure and technologies is still imperative for optimizing the energy performance of each dimension. This not only involves individual improvements but also their integration and connection to boost their collective efficacy. Concurrently, each dimension demands specialized policies and regulations, necessitating an overarching policy assemblage that comprehensively addresses all four dimensions. This holistic approach ensures improvements not just in energy performance, but also across environmental, socioeconomic, and other technical facets.

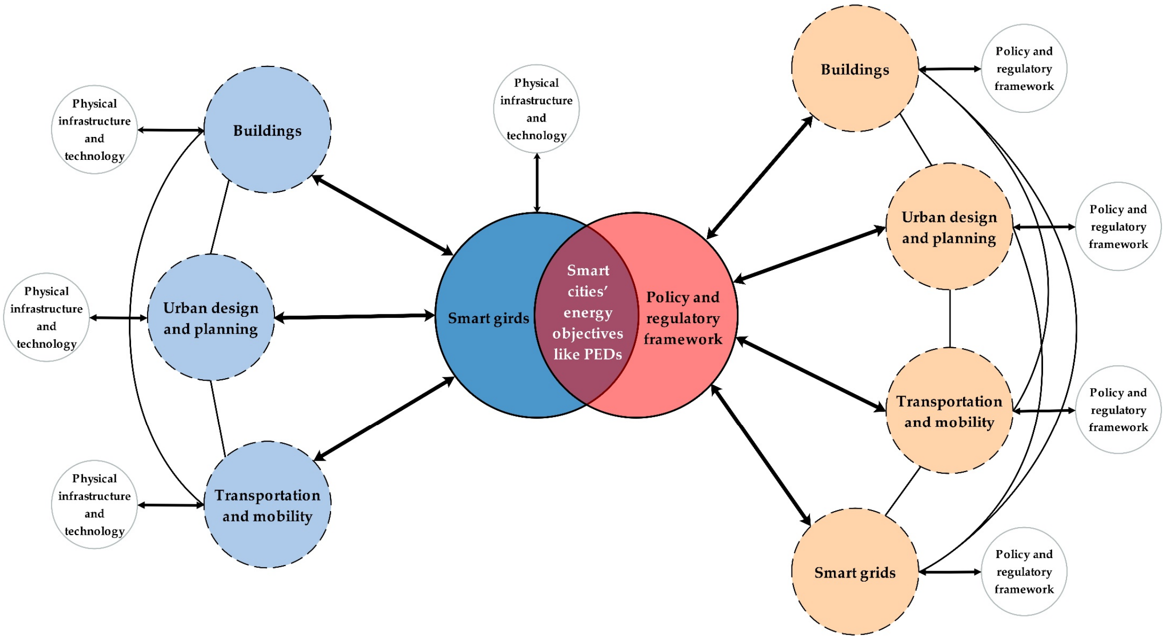

Figure 6. Conceptual framework of the ideal smart city and urban energy planning nexus.

Should smart cities aspire to effectively confront the existing and anticipated challenges in the forthcoming years, strict adherence to the outlined framework becomes crucial. Urban centers are expected to face unprecedented pressures from these global concerns, alongside other emerging uncertainties. In this context, the role of smart cities, especially in the energy sector, emerges as a critical factor in driving sustainable urban energy transitions and climate resilience. This underscores the importance of smart cities as proactive agents in navigating and mitigating the complexities of our evolving environmental landscape [6,86,210]. Therefore, to successfully navigate this endeavor, the next wave of smart city evolution should emphasize an integrative approach developed based on established policies that are flexible, adaptable, and forward-thinking. These policies and regulations should set the stage for a judicious amalgamation of technological prowess with overarching societal and environmental imperatives. In this unfolding chapter, the ultimate success of smart city initiatives will not only hinge on energy efficiency and climate change mitigation and adaptation but also on the ability to embed technology within socially responsive, economically viable, and environmentally sustainable frameworks [28,210].

5.1. Emerging Trends and Concerns

Our review has highlighted a predominant focus within the smart cities literature on leveraging advanced technology systems to achieve broad-based energy use reductions and sustainable energy deployment. However, this emphasis has often been at the expense of fully addressing socioeconomic and environmental considerations. Furthermore, our bibliometric analysis, coupled with insights from recent papers, has revealed key predictions about the future trajectory of research in this domain:

(1) Trend predictions in the realm of smart cities indicate an expected surge in research focusing on the reciprocal impact between smart city initiatives and the environment. It is anticipated that future studies will delve deeper into understanding how these

initiatives can positively influence the environment. This includes exploring the potential for reducing GHG emissions and mitigating UHI effects through the implementation of energy-efficient, solar-powered smart cities [10,211,212]. Additionally, there will likely be a growing emphasis on understanding the adverse environmental impacts of smart technologies, including the ecological footprint of their entire lifecycle, from resource extraction to E-waste disposal [213]. Concurrently, research is expected to intensify in exploring how environmental and climate changes affect smart cities [214]. This includes examining the resilience of smart infrastructures against extreme weather conditions and their capacity to adapt to changing environmental dynamics. Such research could lead to innovations in developing more robust and climate-adaptive smart cities. This dual focus on the interaction between smart cities and their environmental context is poised to play a pivotal role in informing sustainable policy development, energy management, and resilient urban planning in the face of ongoing climatic and environmental shifts [211,212,214].

(2) Socioeconomic justice and inclusion are rapidly gaining attention as key areas of research in smart city development, emphasizing the need for equitable access to energy efficiency and other benefits for all societal segments, particularly marginalized communities [32]. This growth in focus is driven by the recognition that certain populations within digital societies are becoming marginalized due to a lack of technological literacy or economic means, limiting their access to the benefits that smart cities offer [215]. Additionally, it is crucial to ensure that not only the benefits but also any adverse impacts of smart city developments are equally distributed, rather than disproportionately affecting low-income and disadvantaged communities [34,107,188,189]. Research in this area includes exploring mechanisms to ensure the fair distribution of smart city benefits, such as access to green, reliable, and affordable energy, as well as energy-saving technologies and programs [32,191,216]. The goal is to make sustainable energy systems truly inclusive, addressing the disparities in the distribution of incentives and burdens, and ensuring that the advancements in smart cities do not exacerbate existing social inequalities. This concern is increasingly pressing as smart city initiatives advance, highlighting the need for deliberate and targeted strategies to bridge the digital divide and foster a more equitable urban future.

(3) The emerging trend in smart city research is the re-imagination of technology-energy-society relations, with a focus on enhancing public engagement [217]. This approach advocates for the development of smart technologies that not only promote transparency, accountability, and citizen participation but also address privacy and security concerns. Such concerns have been a major barrier to the successful implementation of smart city projects, as hesitancy to participate is often due to a lack of trust. Overcoming these apprehensions is critical for fostering meaningful public engagement [218]. Key to this effort is ensuring the safety and security of citizen data and the accountability of smart technologies. It is essential to involve citizens in decision-making processes, particularly through bottom-up approaches, and to enhance transparency in both the development and management of these projects [219]. Furthermore, educational initiatives that align citizen behavior with energy efficiency objectives are gaining importance [220]. These steps are vital for building trust, fostering community ownership, and making smart city projects more attuned to the needs of their residents.

(4) Future research in the field of smart cities is anticipated to increasingly focus on two interconnected technical and implementation complexities: the integration of advanced technologies, such as 5G and 6G, into urban energy frameworks, and the technical aspects of privacy and security within these complex systems [45,63,65,193,200,201]. This shift reflects a growing need to understand and resolve the challenges of system interoperability, particularly in the context of global technology transfer. This involves navigating a range of financial, geopolitical, and skill-related issues [220]. A critical aspect of this research will be to enhance the technical resilience of smart

city infrastructures against cyberattacks. This includes advancing robust methodologies for ensuring data privacy and maintaining the integrity of energy management systems [45,200,201]. Such research is essential for the development of secure and efficient smart city environments, where the technical safeguarding of information and infrastructure is as crucial as the physical and social dimensions of urban living. By holistically addressing both the integration of cutting-edge technologies and the technical safeguards necessary for security and privacy, future research endeavors are set to significantly impact the design, policy-making, and operational efficacy of smart cities.

5.2. Rethinking Policies and Regulations

The emerging trends and concerns in smart city research highlight the urgent need to reevaluate policy and regulatory frameworks, especially as existing ones may not adequately address the systemic dimensions inherent in smart city development and urban energy planning. This necessitates a shift towards a more integrative approach, one that not only embraces technological advancements but also weaves in considerations of socioeconomic justice, environmental impact, and public engagement. Such an approach recognizes the intricate tapestry of interests among various stakeholders—including governments, urban authorities, residents, investors, and businesses—and underscores the importance of a collaborative approach. Engaging practitioners, policymakers, and academics in dialogue and development is crucial for formulating comprehensive policy and regulatory frameworks that can navigate the promises and challenges of smart cities [221,222].

However, a significant challenge lies in the disparity between rapid technological advancements and slow policy development and performance evaluation. This gap calls for research into the creation of adaptive and responsive policy and regulatory frameworks [204]. Research in this domain should focus on designing policies that are both flexible and robust, capable of keeping pace with technological changes while ensuring effective governance and oversight. Delving into the interplay between emerging technologies and existing legal structures is essential, offering insights into areas where conflict may arise and identifying opportunities for harmonization [191,192]. This line of inquiry is vital to ensure that technological advancements are steered responsibly, benefiting society and the environment.

Acknowledging the dual impact of smart city initiatives on societal and ecological contexts underscores the importance of measurable outcomes in urban energy planning. This recognition necessitates a shift in policy and regulation to not only keep pace with technological innovation but also ensure social and environmental responsibility. In a field marked by uncertainties, like smart cities, every decision carries its own set of trade-offs. Therefore, it is imperative that policies and regulations are designed to accurately measure these trade-offs, enabling a balanced and informed approach to decision-making. Such frameworks are essential for ensuring that smart city initiatives are not only technologically advanced but also aligned with the comprehensive needs of urban energy systems, optimizing outcomes while addressing new challenges and maintaining a commitment to societal and environmental well-being [19,223].

6. Moving beyond This Review

This review provides a foundational synthesis of smart cities in the context of energy and climate objectives, yet it also opens avenues for further exploration. Building upon the insights gained, there is a significant opportunity for expanding the research into detailed case studies of smart cities globally. Such an expansion is not only desirable but necessary to conduct a comprehensive analysis of the performance metrics of smart cities, particularly in terms of their energy efficiency and climate mitigation achievements. Future research could enrich this domain by undertaking comparative analyses of diverse smart city projects and initiatives. This would involve an in-depth examination of the various dimensions discussed in Section 5.1.

Further research endeavors should aim to delineate the unique strategies and challenges encountered by smart cities, taking into account the various geographical, political, environmental, and socioeconomic landscapes they operate within. An area ripe for scholarly exploration involves examining the differential impacts of policy and regulatory frameworks, technological deployments, environmental, and urban planning, and administrative strategies on the progression of smart cities towards their defined energy efficiency and emission reduction targets. A critical analysis of how smart cities have formulated and implemented adaptation and mitigation policies to overcome their faced challenges, and the extent to which these policies have been successful or unsuccessful, is crucial. This analysis should also consider the reasons behind these outcomes, thereby providing a nuanced understanding of the efficacy of smart city initiatives [105,206,224].

Such scholarly inquiries are not only paramount in enhancing our comprehension of the role and effectiveness of policy and regulatory frameworks within the context of smart cities but also crucial in assessing their broader impact on achieving sustainability objectives. This would significantly enrich the discourse on smart cities, providing a foundation for future policy formulation and implementation strategies aimed at optimizing urban environments for energy efficiency and climate resilience.

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Abbreviations

The following abbreviations are used in this manuscript:

PRISMA-ScR	PRISMA Extension for Scoping Reviews
RE	Renewable Energy
AI	Artificial Intelligence
DT	Digital Twin
RS	Remote Sensing
GIS	Geographic Information System
IoT	Internet of Things
IoE	Internet of Energy
IoV	Internet of Vehicles
ITS	Intelligent Transportation System
ICT	Information and Communication Technologies
WoS	Web of Science
DSM	Demand-side Management
UHI	Urban Heat Island
E-waste	Electronic Waste
EVs	Electric Vehicles
V2G	Vehicle-to-Grid
PEDs	Positive Energy Districts

Appendix A

Limitations of Study

While reviewing studies conducted on smart cities and urban energy planning, encompassing its technological, environmental, transportation, and socioeconomic dimensions, we encountered some limitations. Primarily, we grapple with the inherent challenges of selecting pertinent studies and the unavoidable subjectivity infused in data extraction, interpretation, and analysis, inherent to any qualitative review [36]. With transparency at the forefront of the data and paper selection phase, we meticulously detailed our search string, inclusion and exclusion criteria, and the databases employed (WoS), striving for a comprehensive sweep of the relevant literature. Nevertheless, the confines of our established parameters might have resulted in omitting pertinent research, those newly published (after May 2023), inaccessible through our database, or research nestled within specialized reports, policy briefs, professional and practical documents, and other non-academic literature. Therefore, as our review draws predominantly from academic journals, it is conceivable that practical insights or novel strategies from non-academic sectors, including urban policymakers or industry innovators, have been underrepresented.

Regarding subjectivity in data analysis, we used our own analytical categorization and interpretation framework, which inevitably influenced our analysis and findings. The specific framing and design of our review may also be incomplete, potentially leaving out important analytical constructs and categories. The bibliometric review focused on papers published between January 1992 and May 2023. However, the majority of the selected papers for the in-depth review are sourced from the last 5–10 years. This emphasis is reasonable due to the substantial volume of recent publications and the importance of reviewing and analyzing current knowledge and research findings. Moreover, the deployment of VOSviewer software, pivotal for our bibliometric analysis, brings its inherent constraints to keyword extraction and semantic apprehension, potentially curtailing nuanced interpretations. Additionally, although Section 4 focuses on five key dimensions and thoroughly investigates their promising and challenging sides, there might be emerging or niche topics, technological advancements, or other challenges, concerns, and barriers that were not covered throughout this review.

To overcome these limitations, we developed a comprehensive research protocol that includes explicit review questions, well-established search strings, and criteria for inclusion and exclusion. Our approach adheres to the checklist requirements for PRISMA-ScR analyses and provides justification for the decisions made at each stage of the review process. Four authors independently evaluated both search strings and results before reaching a consensus collectively to mitigate subjectivity during paper selection. To minimize the possibility of excluding relevant studies, we extensively included and scrutinized a substantial number of papers (193 records), far surpassing what is typically seen in other existing reviews in this field. Moreover, in the initial phase of the review, we identified and utilized 19 highly relevant reports and documents (Appendix B). These sources helped define our search strings and informed our recommendations for future research. This approach was necessary because smart cities and urban energy planning are not simply academic concepts; to effectively integrate smart city initiatives into improving urban energy profiles, it is crucial to establish a mutually beneficial relationship between theory and practice.

Appendix B

Table A1. The list of reviewed non-peer-reviewed documents and reports.

#	Organization	Documents	#	Organization	Documents
1	European Commission	1-Summary Report on Urban Energy Planning: Potentials and Barriers in Six Cities 2-Strategic Energy Technology (SET) Plan ACTION n°3.2 Implementation Plan 3-Digitalization in Urban Energy Systems: Outlook 2025, 2030 and 2040	8	MIT SENSEABLE CITY LAB projects	12-The Smart Enough City: Putting Technology in Its Place to Reclaim Our Urban Future
2	International Energy Agency (IEA)	4-Digitalization & Energy 5-Energy Technology Perspectives 2023 6-Empowering Cities for a Net Zero Future: Unlocking Resilient, Smart, Sustainable Urban Energy Systems	9	Arup	13-Five Minute Guide: Energy in Cities
3	United Nations University, UNU-EGOV, International Development Research Centre Canada (IDRC)	7-Smart Sustainable Cities—Reconnaissance Study	10	IBM Institute for Business Value Executive Report	14-Smarter Cities for Smarter Growth
4	European Parliament	8-Digital Agenda for Europe	11	ASEAN Smart Cities Network and ASEAN Secretariat (ASEC)	15-ASEAN Smart Cities Planning Guidebook
5	American Public Power Association	9-Creating a Smart City Roadmap for Public Power Utilities	12	OECD	16-Measuring smart cities' performance: Do smart cities benefit everyone? 17-Enhancing the Contribution of Digitalization to the Smart Cities of the Future
6	International Renewable Energy Agency (IRENA)	10-World Energy Transitions Outlook 2023: 1.5 °C Pathway	13	World Economic Forum	18-Electric Vehicles for Smarter Cities: The Future of Energy and Mobility
7	C40 CITIES Climate Leadership Group	11–10 Climate Challenges & Plenty of Solutions	14	Deloitte	19-Renewables (em)power smart cities

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