AI and 5G Integration for Smart City Energy Systems: A Systematic Literature Review

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***Abstract*—Smart cities increasingly rely on Artificial Intelligence (AI), 5G, and Internet of Things (IoT) technologies to enhance energy management and support real-time decision-making in smart grids. This study presents a systematic literature review of recent research on the integration of AI and 5G in urban energy systems, with a focus on sustainability goals. It examines how these technologies are used for renewable energy integration, demand-side control, and predictive maintenance across smart environments. Using data from OpenAlex, Scopus, and Web of Science covering the period 2018 to 2025, the review was filtered by language, domain, and scientific relevance. Key findings reveal the use of machine learning models for forecasting, anomaly detection, and system optimization. The review also identifies technical, ethical, and infrastructural challenges, including data heterogeneity, limited interoperability, and regional inequalities in deployment. While AI and 5G offer promising capabilities for real-time monitoring and system automation, the literature shows persistent gaps in algorithm robustness and standardized integration frameworks. The paper emphasizes the need for validated, scalable solutions to achieve long-term energy sustainability. This review provides a clear overview of current trends and future directions in smart energy systems, contributing to a better understanding of how digital technologies shape the future of sustainable urban infrastructures.**

Keywords*—Smart cities; artificial intelligence; 5G; energy management; smart grids; renewable energy integration; IoT; machine learning; sustainability

I. Introduction

The rapid growth of the global urban population has brought urgent challenges in energy management, infrastructure stability, and operational flexibility. In response, the concept of smart cities has emerged, integrating advanced digital technologies to improve the efficiency and quality of urban services [2], [11]. Among the key enablers of this transformation, artificial intelligence (AI) and fifth-generation (5G) communication networks play a central role in reshaping energy systems to support sustainable urban development [9], [30].

Smart energy systems in urban environments depend on smart grids, intelligent buildings, IoT-connected devices, and distributed renewable energy sources [3], [14]. These systems require real-time monitoring, adaptive control, and future-oriented optimization capabilities increasingly supported by AI for prediction, anomaly detection, and intelligent energy flow management [19], [21], [24]. In parallel, 5G offers ultra-low latency and high-speed connectivity, enabling the instantaneous transmission of data across edge devices and cloud platforms, thereby supporting large-scale deployment of IoT-based control systems [23], [26], [31].

Despite their potential, the integration of AI and 5G in energy systems remains limited by technical and ethical barriers. Challenges include system fragmentation, lack of standardized protocols, scalability of algorithms, data heterogeneity, cybersecurity concerns, and uneven access to infrastructure across regions [9], [17], [30], [33], [34]. These gaps hinder the development of comprehensive frameworks capable of addressing energy performance, social equity, and long-term sustainability.

This study addresses these concerns by conducting a systematic literature review of publications indexed in OpenAlex, Scopus, and Web of Science, covering the period from 2018 to 2025. The objective is to assess how AI and 5G are integrated into smart city energy systems, identify their contributions and limitations, and explore future directions. The review is structured around the following research questions:

RQ1: How are AI and 5G used in smart city energy systems?

RQ2: What technical and ethical issues limit their integration?

RQ3: How is their impact on energy performance evaluated?

RQ4: What are the benefits and outcomes of AI-enhanced energy management in smart cities?

By addressing these questions, the study offers a structured understanding of the evolving role of AI and 5G in smart energy systems, highlighting both current contributions and the areas requiring further innovation and policy attention.

II. Methodology

During this study, we follow a systematic and data -driven method to ensure accurately and relevance in our findings. Fig. 1 emphasizes the five main steps in our research process. The first phase defines the scope of the study,with a focus on how artificial intelligence and 5G technologies contribute to the energy dimension of smart cities. In phase 2, we collect literature from three large scientific platforms - Openlex, Web of Science and Scopus - advanced filtration strategies.

For OpenAlex, we processed the search using a combination of technical keywords such as “Energy” and “Smart”, and limited the results to open access tasks published between 2018 and 2025. We did not exclude - related domains such as drugs, psychology, chemistry and humanities to focus specially related to engineering. We also limited the selection from articles and book chapters related to IoT, Edge/Fog Computing, Smart System and AI-based urban technologies, and banned the language in English.

Step 3 includes inclusion criteria based on quality, relevance to energy domains and screening of extracted studies using AI and clear links for 5G integration. In Step 4, we use a thematic classification and bibliometric mapping to detect recurrent applications, technical barriers and regional contexts. Finally, phase 5 highlights the most important research contribution to applying AI and 5G to smart energy infrastructure in urban references, highlighting existing intervals and future instructions.

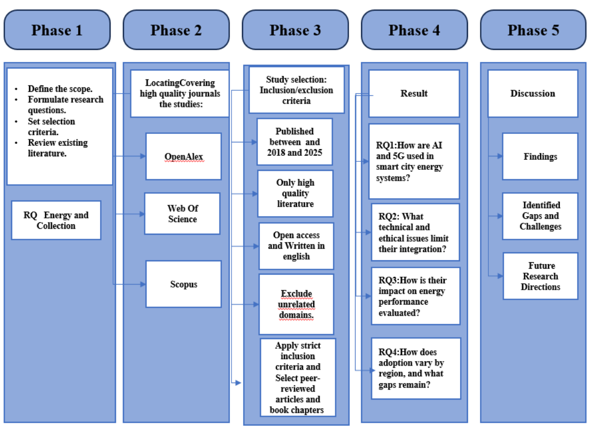

Fig. 1. Research process.

To continue the recovered literature base, we organized a descriptive book list of the final dataset. As shown in Fig. 2, the literature extends from 2018 to 2025 and includes a total of 1,350 documents from 570 different places of publication. These documents were written by 4,413 contributors, with an average of 3.62 co-author per paper, indicating a high level of cooperation research in the region. In particular, 33.78 percent of publications include international co-authors, reflecting global relevance and multi-creked interest in AI and 5G-based energy systems. The dataset contains 203 single author tasks, while the total number of references cited in all documents reaches 31,511, and emphasizes the depth of scholars and the prosperity of analyzed corpus. The average document age is 3.39 years, suggesting that the corpus is reflected in order to develop both recent and developed research mobility. In addition, the average quotation time per document is 16.22, which confirms the important education effect. Finally, we identified 546 separate author keywords, which act as a semantic foundation for thematic grouping and trend analysis in the later stages of this study.

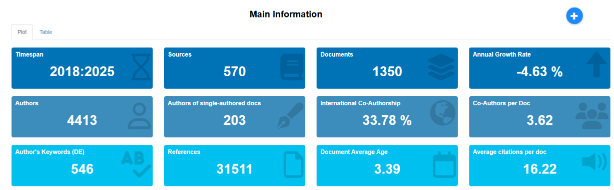

Fig. 2. Main information.

III. Results

Smart cities embody a modern strategy for urban development that leverages information and communication technologies (ICT) to make Urban more comfortable, durable and effective [1] [2]. At their core, smart cities aim to ensure a clean, cost-effective, and secure living environment for the citizens to live, work and play by organizing different systems, including energy, water, transport, public health and safety as showing in Fig. 3 [3].

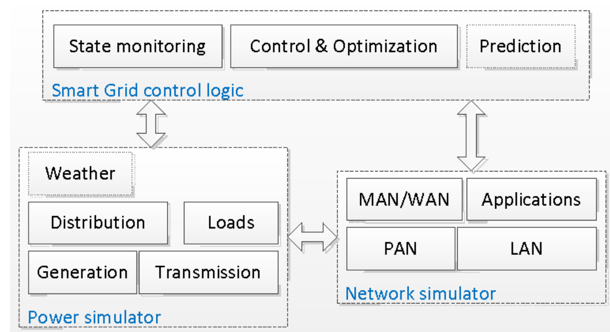

Fig. 3. Overview of a standard smart grid co-simulation environment.

The infrastructure of smart cities relies on a combination of interconnected technologies and subsystems. This includes smart grids, intelligent mobility solutions, adaptive traffic control, automated waste management, smart infrastructures, and systems for environmental monitoring [4]. The Internet of Things (IoT) plays an essential part by supporting real-time data collection and intelligent context-driven processing via interconnected sensors and actuators [1] [5].

The idea of smart urban control has developed with the emergence of recent technology which includes IoT, statistics analytics, and artificial intelligence [6] [7] [8]. These technology enable the optimization of strength intake, integration of renewable energy sources, discount of greenhouse gasoline emissions, and improvement in universal best of urban life [9][10] as showing in Fig. 4.

Smart city applications integrate artificial intelligence, data analytics, and advanced learning algorithms to enhance urban living standards for large populations [11] [12] The present and anticipated development of smart cities is marked by the convergence of various technologies, including 5G and blockchain infrastructure, which are expected to strengthen decision-making capabilities, anticipate urban dynamics, and support advanced IoT functionalities [13].

Smart city platforms support the collection and unified analysis of data originating from heterogeneous sources, in-

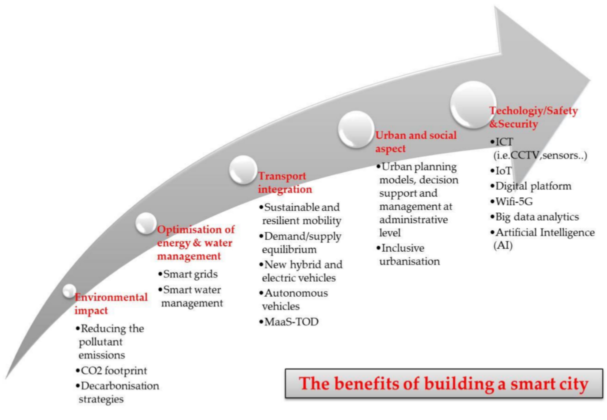

Fig. 4. The benefits of the spread of smart cities.

cluding systems for traffic observation, energy usage tracking, and environmental data sensing [14] [15]. This data -driven approach to city rule optimizes the operation and distribution of resources, and eventually leads to high energy efficiency and productivity.

Energy infrastructure plays an important role in smart cities, as all other urban works will eventually be closed if the energy is not available for a significant period [3]. Cities aim to build intelligent energy systems that support adaptive lighting, automated building systems, smart transport solutions, and energy distribution networks [16] as showing in Fig. 5.

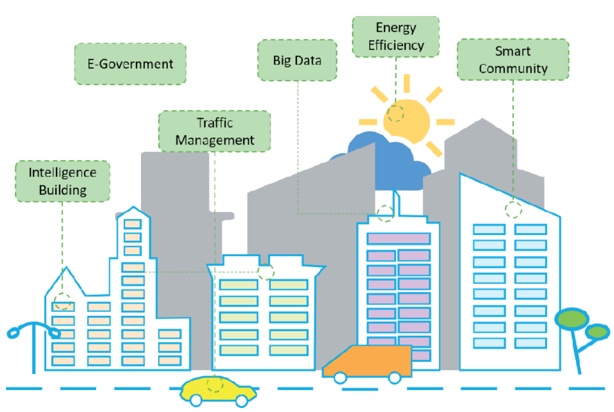

Fig. 5. Basic components of smart city.

Original research on smart cities focused on the principle, probe, design, development and implementation of smart, flexible and urban environments with low carbon. This included research on areas such as ICT and intelligent infrastructure, smart grid, energy -dense buildings, climate change mitigation, decision support systems and machine learning for machine learning for IoT, Big Data, AI and environmental and environmental [4].

A. Smart Cities and Energy Management

Energy management is among the most critical challenges of developing smart cities, which acts as the basis that all other urban functions depend on study [3]. The purpose of smart cities is to develop intelligent energy infrastructure that creates efficiency, increases economic growth and improves the quality of life through functions such as smart street lighting, intelligent buildings, smart mobility and power grid [16]. As part of the concept of “smart and sustainable cities,” two flagship applications have emerged worldwide: smart electricity grids that promote renewable energy sources, and efficient mobility solutions that reduce automobile use and greenhouse gas emissions [17] A smart grid is one of the essential elements of smart city systems, alongside other intelligent infrastructure elements such as smart traffic lights, mobility solutions, buildings, waste management, and environmental monitoring [18].

Through self-healing designs, automation, and remote monitoring and control, smart energy grids modernize power systems. As a result of these systems, consumers will be able to make informed decisions and be able to safely integrate distributed renewable energy resources in order to improve overall energy efficiency [3]. In the context of future smart energy systems, algorithms are expected to infer user needs and consumption patterns by analyzing historical data, optimize and control the interconversion and distribution of energy vectors while taking engineering constraints and policy objectives into consideration [19].

Multi-energy vectors such as electric power, heat, and gas in urban environments enable integration of energy subsystems and support real-time operational control [19]. As embedded algorithms are increasingly deployed across multiple layers of the energy network, ranging from smart meters to real-time monitoring units, machine learning and intelligent computing tools are gaining relevance in supporting autonomous decision processes and adapting to evolving system behavior [19].

Modern smart city energy frameworks uses cutting-edge technology and data analytics to align and manage multiple urban infrastructures with the aim of increasing energy performance and operational output [14]. Smart grids are a key initiative to control energy consumption and optimize energy distribution, and integrate renewable energy technologies such as photovoltaic systems and wind energy converters within urban systems [14]. In smart cities, advanced smart grid frameworks are under development to address energy management challenges, including transactions and autonomous vehicle charging. [20]. These frameworks make use of a variety of technologies to enhance energy efficiency [20] as showing in Fig. 6, including deep learning, linear optimization, semantic technologies, and simulation. To integrate Information and Communication Technologies into urban development, smart cities adopt innovations including technologies like IoT, AI, Geographic Information Systems, digital twin models, remote sensing systems, intelligent transport infrastructure, and advanced energy grids [9] By implementing these tools, urban life is improved by reducing greenhouse gas emissions, optimizing energy consumption, incorporating sustainable energy inputs and lowering greenhouse gas emissions [9][10].

B. AI and Machine Learning Applications in Smart City Energy Systems

Artificial intelligence (AI) and machine learning (ML) are becoming increasingly vital for automated decision-making and responding to changes in energy system dynamics as embedded algorithms become more pervasive throughout energy

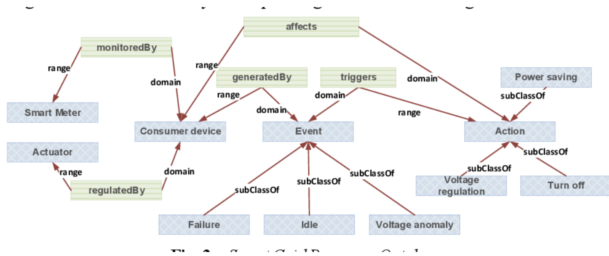

Fig. 6. Smart grid response ontology.

networks [19]. The concept of future smart energy systems includes autonomous algorithms capable of extracting user demand patterns and consumption behaviors from past data records, manage and coordinating the conversion and distribution processes of multiple energy carriers, while at the same time considering engineering constraints and policy objectives [19].

In smart city energy management, AI and ML applications are being leveraged for multiple purposes. Data-driven smart grid frameworks employ deep learning, linear optimization, semantic technology, and simulation to address complex energy management challenges including energy trading and autonomous vehicle charging [20]. As a result of these technologies, billions of people in urban areas are able to live more sustainably and improve their quality of life [11].

Optimization of renewable energy sources is one of AI's most significant contributions, which reduces carbon emissions and improves energy efficiency [21] [22]. With artificial intelligence and 5G technologies, energy providers are able to predict renewable energy production, such as when the sun will shine or the wind will blow, and adjust energy supply accordingly [23].

AI-driven smart grids enhance operational efficiency by dynamically adjusting to variations in energy supply and demand by leveraging real-time data analysis and adaptive learning algorithms, ensuring more stable and efficient distribution networks [21] [24] A smart building using AI-powered systems to forecast energy needs, improve the management of heating and cooling operations, and enhance the integration of renewable energy sources [21].

Several reviewed studies assess the energy-related impact of AI and 5G integration using quantitative indicators such as energy savings, carbon emission reductions, load balancing efficiency, and response time to peak demand. Evaluation methods include simulation-based energy modeling, real-time sensor data analysis, and predictive accuracy of AI-based demand forecasting systems. These metrics provide objective evidence of improved system performance and support the deployment of intelligent energy infrastructure in urban environments.

Besides energy management, machine learning, deep reinforcement learning, and artificial intelligence are being used in smart cities to develop intelligent transportation systems, cybersecurity, and 5G networking services. [25]. In transportation, AI and 5G can help reduce traffic congestion and emissions by optimizing traffic flow and identifying the most efficient vehicle routes, thereby decreasing time spent on the road and saving energy [23].

Researchers are addressing energy management challenges through a combination of IoT, 5G, and cloud computing, along with machine learning and deep learning approaches [26] [27]. Currently, researchers are working on developing algorithms for autonomously analyzing, predicting, and managing energy consumption in smart buildings and cities [28].

As artificial intelligence technology continues to develop, smart cities will apply AI more widely across intelligent transportation systems, energy management, and public safety to achieve more efficient urban management and services [29]. Despite the challenges regarding ethics and data management, AI is having a multi-dimensional impact on smart cities, affecting not only energy management, but also transportation and citizen engagement[30].

The evolution of smart cities has been supported by fundamental and applied research focused on AI and ML applications for environmental sustainability and climate change [4]. This research has laid the groundwork for current and future applications of these technologies in optimizing urban energy systems.

C. 5G Technology's Role in Smart City Energy Management

Smart city energy management systems depend on 5G wireless networks, which form the backbone of advanced energy systems.With 5G, IoT devices can communicate seamlessly and instantly, enabling real-time monitoring and control of energy assets across urban areas due to its ultra-low latency and high-speed connectivity [31]. As a result of enhanced connectivity, energy systems are more efficient and sustainable, particularly in applications such as smart grids, smart buildings, and intelligent transportation systems [31].

The integration of 5G with IoT technology creates powerful synergies for energy management in smart cities. Combining these technologies facilitates fast data transmission between communication channels and cloud storage, enabling efficient data retrieval and analysis for energy optimization [26] [27]. In renewable energy applications, 5G's instantaneous communication capabilities allow energy providers to quickly adjust their supply in response to AI predictions about solar and wind availability [23] as showing in Fig 7.

In addition to enhancing energy generation and distribution, 5G technology enhances transportation efficiency within smart cities, which impacts energy consumption overall. By optimizing traffic flow and identifying the most efficient routes for vehicles, 5G-enabled systems reduce congestion, reduce traffic time, and decrease emissions [23]. This demonstrates how 5G's benefits extend beyond direct energy management to address broader energy consumption patterns in urban environments.

The deployment of 5G networks promises to further enhance connectivity and enable more sophisticated IoT applications throughout smart cities [13]. As part of a wide spectrum of information technologies being applied to improve urban "smartness," 5G works alongside artificial intelligence, big data analytics, cloud computing, and IoT to create more responsive and efficient energy systems [32]. The continued evolution of these communication networks will play a pivotal role in the future development of smart city energy management, providing the connectivity required for increasingly complex and integrated urban systems.

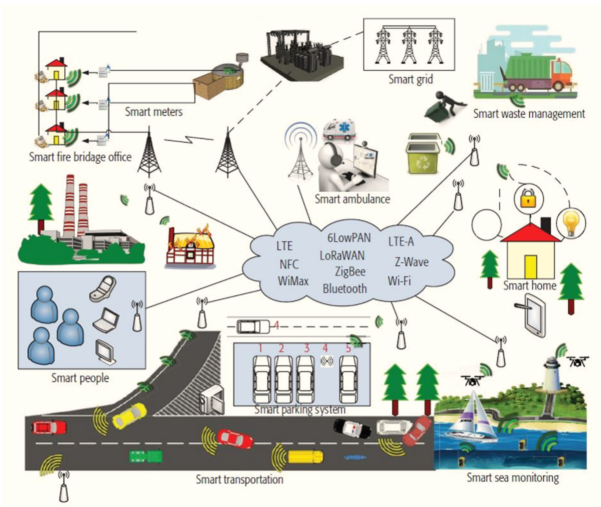

Fig. 7. Available communication technologies in various applications for smart cities.

D. Validation and Comparative Analysis with Existing Reviews

To enhance the scientific robustness of our study, we conducted a comparative validation by analyzing how our findings align with or extend those of recent systematic reviews addressing AI, 5G, and smart city energy systems. This approach confirms the coherence of our results while identifying the distinct contribution of our work.

Several prior studies have addressed parts of this research landscape. Bibri presented an integrated view of AI, IoT, and Big Data in sustainable smart cities, emphasizing technological convergence but overlooking infrastructure scalability and regional inequalities. O'Dwyer's review explored the role of AI in energy systems aligned with sustainability goals but did not incorporate 5G technologies or joint AI-5G integration frameworks. Santos examined the ethical and technical challenges of AI in smart cities, yet lacked consideration of telecommunication infrastructures essential for real-time operations. Camacho focused on AI-driven energy management but provided limited insights into system interoperability and IoT-5G data integration.

In contrast, our review takes a dual-focus approach that simultaneously addresses AI and 5G within smart energy systems. We offer a broader perspective that includes:

A combined analysis of technical and ethical challenges,

Regional disparities in deployment and access,

The need for real-time system responsiveness, algorithm robustness, and cross-platform interoperability.

Table I presents a structured synthesis of this comparative analysis. It clearly situates our contribution within the broader research context and highlights specific gaps in prior work that our study addresses.

IV. Discussion

A. Fragmentation Between Technological Layers

One key observation from the literature is the persistent disconnect between the development of artificial intelligence (AI) models and the implementation of 5G communication systems within smart city energy initiatives. Most studies concentrate on one isolated component. Some optimize machine learning algorithms for forecasting energy consumption or production. Others evaluate the performance of communication infrastructures, focusing on throughput, latency, or coverage.

Very few works integrate these components into a coherent, real-time energy management architecture. This siloed approach results in technical inconsistencies. For example, AI models are often designed without considering the limitations of underlying network infrastructures, which may not support the real-time data flows required. Conversely, 5G networks are sometimes deployed without embedding intelligent processing capabilities, limiting their contribution to autonomous decision-making.

This lack of integration across technological layers hinders the deployment of closed-loop, adaptive energy systems. Without synergy between AI and 5G, smart city platforms struggle to deliver timely, efficient, and scalable energy management in real-world environments.

B. Limited System-Level Evaluations

A recurrent issue across the reviewed studies is the limited presence of system-level validation. Most contributions focus on the performance of algorithms using isolated datasets or simulations conducted under fixed, controlled conditions. While these works are often rigorous in their methodological design, they neglect the complexities of real-world deployment.

There is little effort to assess the full data pipeline—from sensor-level data acquisition to transmission over 5G networks, edge processing, and final decision-making through AI models. The absence of integrated benchmarks reflecting interactions among these components limits the evaluation of key operational metrics such as scalability, resilience, and fault tolerance.

Without such validations, it becomes difficult to determine whether proposed solutions can maintain stability and responsiveness under realistic urban energy demands. This gap weakens the practical impact of many research efforts and hinders progress toward deployable, intelligent energy systems.

C. Underexplored Edge Intelligence Scenarios

Edge computing is widely acknowledged as a critical component for enabling distributed intelligence in smart energy systems. However, few studies propose concrete system architectures that effectively leverage edge nodes to reduce latency and optimize energy usage. The majority of contributions remain anchored in cloud-centric models, which can lead to communication overheads and increase the risk of delays in time-sensitive operations.

Despite its theoretical advantages, the integration of edge AI in energy-related use cases remains poorly formalized. The literature lacks structured frameworks for distributing AI

TABLE I. COMPARATIVE SUMMARY OF SELECTED LITERATURE REVIEWS

Author	cm**Scope of Review**	**Technology Focus**	**Main Gaps Identified**	**Limitations**
Bibri	cmSmart cities and sustainability	AI, IoT, Big Data	Ethics, convergence	No focus on regional disparities or scalability
O'Dwyer	cmSmart energy systems and sustainability	AI	Infrastructure, policies	No mention of 5G or real-time integration
Santos	cmAI challenges in smart sustainable cities	AI	Technical and ethical	Does not link with communication infrastructure
Camacho	cmAI for energy management in smart cities	AI	Algorithm limitations	Limited analysis of IoT/5G integration
Our review	cmAI and 5G in smart city energy systems	AI + 5G + IoT	Scalability, ethics, region	Integrated and comparative approach

tasks between edge and core nodes. In particular, there is limited work on adaptive task allocation strategies that consider dynamic factors such as local energy demand, network congestion, and the uncertainty of AI predictions.

This shortfall limits the development of responsive, low-latency energy systems capable of autonomous decision-making close to the data source.

D. Geographic and Contextual Imbalance

The geographic scope of the reviewed studies reveals a strong concentration in high-income countries with advanced technological infrastructures. These contexts often benefit from stable connectivity, standardized hardware, and supportive regulatory environments. In contrast, urban energy systems in low and middle income regions where networks are less reliable, devices are more heterogeneous, and policies are often fragmented remain largely absent from the literature.

This imbalance reduces the external validity of current research. Solutions optimized for well-resourced environments may not scale or adapt to settings with infrastructural and institutional constraints. To enhance applicability, future work must incorporate context-sensitive approaches that account for disparities in connectivity, device interoperability, governance models, and energy usage profiles.

E. Methodological Diversity and Lack of Convergence

The literature demonstrates a broad methodological range, encompassing supervised learning, reinforcement learning, federated approaches, and hybrid architectures. However, this diversity is not accompanied by standardized evaluation metrics or deployment protocols. The lack of convergence in assessment criteria makes cross-study comparisons unreliable and limits the identification of effective design patterns.

This fragmentation also poses challenges for reproducibility. Without shared benchmarks or experimental frameworks, replicating and validating results becomes complex, slowing down methodological refinement and large-scale adoption.

Advancing the field requires the adoption of common evaluation protocols, multi-criteria performance assessments, and the availability of open-access datasets to support fair benchmarking and collaborative development.

F. Gaps and Challenges in Smart City Energy Systems

Despite the promise of smart city energy systems, several critical gaps and challenges remain to be addressed:

Interoperability and Complexity of the System: In smart cities, interconnected tools, platforms, and sensors pose a challenge, but interoperability must be ensured [9]. Integration of various technological components requires standardized protocols, which are not yet fully established across all systems.

Management and Analysis of Data: Smart city infrastructure generates a great deal of data that presents significant challenges for gathering and analyzing [9]. Due to its volume, velocity, and variety, advanced processing capabilities are needed beyond what is currently available. Security and Privacy Concerns: As smart energy systems collect more and more data, privacy and security concerns must be addressed [9].

Algorithm Limitations: Existing studies often fail to address the full complexity and uncertainty of real-world scenarios in energy optimization, creating a gap between theoretical models and practical implementation [33].

Implementation of Advanced Algorithms: The energy consumption of smart buildings and cities still requires more sophisticated algorithms capable of automatically analyzing, predicting, and managing it [28].

AI Implementation Gaps: Technological gaps exist specifically when implementing artificial intelligence in smart cities, affecting the potential optimization of energy systems [34].

System Flexibility and Resilience: Renewable energy sources are becoming more prevalent, and modern energy management solutions do not offer the flexibility and resilience required to adapt to changing energy landscapes [28].

Integration of Renewable Energy: The integration of renewable energy sources into existing infrastructure remains a significant challenge for smart cities despite their desire to integrate renewable energy sources [9].

Comprehensive Energy Optimization: Despite advances in evolutionary algorithms and deep reinforcement learning, there is a need for more comprehensive and robust solutions for smart city energy operations that can handle real-world complexities [33].

Coordination Across Urban Systems: Achieving the holistic approach particular to smart cities requires coordinated and integrated social, environmental, and economic interventions across multiple sectors, presenting significant coordination challenges [9] [10].

G. Sustainability and Long-Term Perspectives

Sustainability concerns remain largely overlooked in the reviewed literature. Key aspects such as the energy consumption of AI models, the carbon footprint of 5G infrastructure, and the lifecycle impact of deployed systems are rarely quantified or integrated into system design. This omission is critical, given that smart cities are expected to reduce emissions and promote energy efficiency.

There is a contradiction between these objectives and the current lack of energy-aware intelligence. Most AI-5G solutions are evaluated in terms of performance, with minimal attention to their environmental cost.

Future work should prioritize the development of resource-efficient AI models and establish methodologies for assessing the ecological impact of intelligent infrastructures. Embedding sustainability into design choices is essential to ensure long-term viability and alignment with climate goals.

V. Conclusion

This review explored the integration of artificial intelligence and 5G technologies into smart city energy systems through a systematic analysis of recent literature. The study identified their core applications in predictive analytics, load optimization, demand forecasting, and energy automation. AI contributes to real-time decision-making, while 5G ensures fast, reliable communication for distributed systems. Technical and ethical challenges remain, including algorithm transparency, data quality, privacy concerns, and unequal access to infrastructure. Evaluation methods found in the literature include simulation modeling, energy performance indicators, and predictive accuracy metrics.

Despite these advancements, several gaps persist regarding interoperability, standardized frameworks, and large-scale deployment. Future research should address cross-platform integration, improve data-sharing protocols, and validate models with real-world urban data. There is also a need to explore AI and 5G synergies in dynamic contexts such as mobility-energy coupling and disaster-resilient infrastructures. This study provides a roadmap for researchers and urban planners seeking to build energy-efficient, responsive, and sustainable cities using intelligent technologies.

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