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Revolutionizing Energy Management and Smart City Development with Artificial Intelligence and Blockchain

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ABSTRACT

Smart cities leverage advanced technologies such as the Internet of Things (IoT), big data analytics, and automation systems to enhance the quality of life, improve resource efficiency, and reduce operational costs. Effective management of critical infrastructures, including power and energy networks, intelligent transportation, urban services, and data security, is still a significant challenge in the development of these cities. Artificial Intelligence (AI), with its extensive capabilities in big data analysis, energy consumption forecasting, power distribution optimization, and intelligent transportation management, plays a pivotal role in facilitating decision-making processes and enhancing the efficiency of urban systems. Meanwhile, blockchain technology provides a decentralized infrastructure, ensuring transaction transparency and enabling the execution of smart contracts, thereby guaranteeing security and trust in energy data and urban service management. This paper presents a comprehensive review of AI and blockchain applications in power systems and smart cities, analyzing their benefits and limitations, and identifying future research directions. The findings indicate that integrating these emerging technologies can substantially improve network efficiency, reduce operational costs, enhance security, and support sustainable energy management, ultimately contributing to the achievement of sustainable development goals in smart cities. Additionally, challenges related to scalability, interoperability between technologies, as well as legal and regulatory issues are discussed to provide a clear outlook for future research endeavors.

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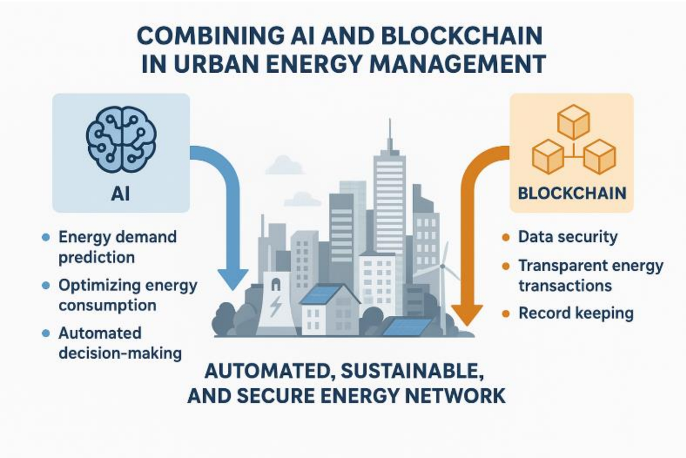

Figure 1. Combining Artificial Intelligence and Blockchain in Urban Energy Management

1. Introduction

With the rapid growth of urban populations and the consequent surge in energy demand, urban resource management has evolved into a multifaceted and pressing challenge. As more than half of the world's population now resides in urban areas, the complexity of managing resources particularly energy has increased significantly. Traditional power grids, often rigid and centralized, are increasingly inadequate to meet the dynamic needs of modern urban environments. To address these challenges, the concept of smart cities has emerged, aiming not only to enhance citizens' quality of life but also to improve the overall efficiency, resilience, and sustainability of urban systems through the deployment of advanced technologies.

A critical and foundational element of smart cities is the development and implementation of smart power grids and sophisticated energy management systems. These systems must possess the capability to dynamically adapt to the highly variable patterns of energy consumption and production that characterize urban settings. According to Badidi et al. (2022), such adaptability is essential for balancing supply and demand in real-time, integrating renewable energy sources, and minimizing energy wastage. In this context, artificial intelligence (AI) plays a pivotal role by leveraging its ability to process vast amounts of data, extract meaningful patterns, and generate highly accurate forecasts. AI techniques have been successfully applied to various aspects of energy management, including energy demand forecasting, load pattern recognition, optimization of power generation, and the management of intelligent transportation systems (Garg et al., 2024; Zekić-Sušac et al., 2021). These applications not only improve operational efficiency but also contribute to reducing carbon footprints, a critical objective in the global fight against climate change (Lobus et al., 2023). Figure 2 provides a schematic view of smart energy systems, illustrating the role of AI and blockchain

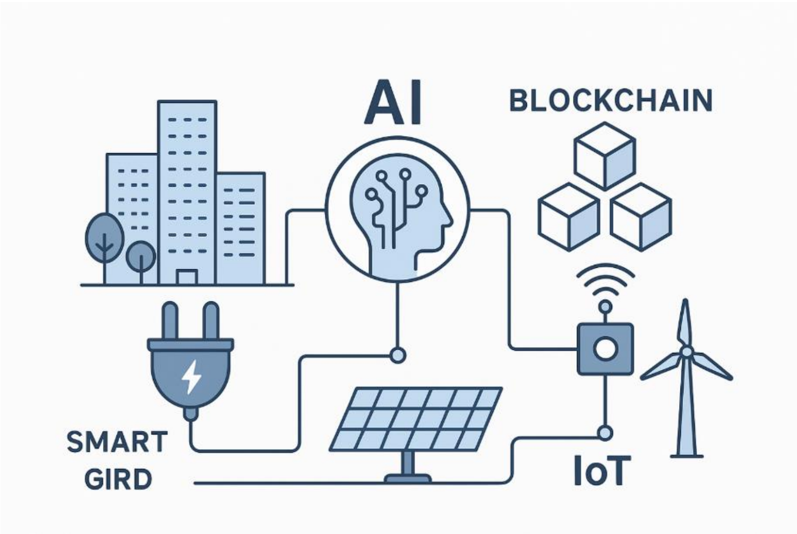

Figure 2. Making Energy Smart in Cities Using AI and Blockchain

In parallel, blockchain technology has gained increasing attention as a transformative tool for enhancing data security and transparency within smart city infrastructures. As a decentralized and immutable distributed ledger system, blockchain facilitates secure and transparent recording of transactions and data exchanges. Andoni et al. (2019) emphasize that blockchain technology can enable smart contracts between energy producers, consumers, and service providers, thereby reducing operational costs, mitigating fraud, and building trust among stakeholders in energy markets. This transparency is particularly important in decentralized energy trading platforms, where peer-to-peer energy exchanges require robust and tamper-proof verification mechanisms. Furthermore, blockchain's integration with IoT devices in urban environments can enable real-time monitoring and automated response systems, fostering more responsive and resilient urban energy networks (Al-Fuqaha et al., 2015; Zhao et al., 2023).

Despite these technological advancements, the combined application of AI and blockchain in urban energy management remains an emerging field with notable research gaps. While AI provides data-driven decision-making and predictive capabilities, blockchain ensures data integrity and secure transactions. Their convergence holds the potential to establish automated, sustainable, and secure energy networks (Al Shareef et al., 2024). However, challenges such as system interoperability, blockchain scalability, and real-time data processing remain largely unresolved (Dritsas et al., 2024; Jeyaraj et al., 2025; Saidu et al., 2025).

Overall, this study provides a comprehensive and cross-disciplinary analysis of the applications of artificial intelligence and blockchain in urban energy management and smart cities. It demonstrates that the integration of these technologies can significantly enhance energy efficiency, improve security, and promote urban sustainability. By examining the benefits and existing limitations, this research also highlights future research directions and guides policymakers and practitioners toward effective and feasible implementations. Consequently, it offers a coherent understanding of the complementary role of AI and blockchain in the development of smart cities and urban energy management.

2. Methodology

This study aims to provide a systematic review of the synergistic applications of artificial intelligence (AI) and blockchain technology in power systems and smart cities. To achieve this goal, a structured methodology was designed and implemented, consisting of the following stages:

2.1. Database Selection

Considering the interdisciplinary nature of the topic, searches were conducted across several major scientific databases, including IEEE Xplore, Scopus, Web of Science, ScienceDirect, SpringerLink, and the ACM Digital Library. These databases cover a wide spectrum of publications in electrical engineering, computer science, energy systems, and smart city research. Additionally, supplementary searches were performed using Google Scholar to ensure comprehensive coverage and minimize the risk of missing relevant studies.

2.2. Search Strategy

To maximize the retrieval of relevant studies, combinations of core keywords and their synonyms were applied to article titles, abstracts, and keywords. Primary search terms included: "Artificial Intelligence," "Machine Learning," "Deep Learning," "Blockchain," "Distributed Ledger," "Smart Grid," "Smart City," "Energy Management," "Peer-to-Peer Trading," and "IoT Urban Services." The search was limited to publications from 2010 to 2025 to include both foundational and recent studies.

2.3. Inclusion and Exclusion Criteria

To ensure the relevance and quality of selected studies, explicit inclusion and exclusion criteria were defined:

Inclusion criteria:

1. Studies published in peer-reviewed journals or reputable conference proceedings.
2. Research directly or indirectly addressing the applications of AI and/or blockchain in power systems or smart city infrastructures.
3. Articles presenting a methodology, analytical framework, or case studies with practical relevance.

Exclusion criteria:

1. Non-scientific sources, industrial reports, or non-peer-reviewed materials.
2. Studies focusing solely on AI or blockchain without connection to power systems or smart city applications.
3. Publications without access to full text.

2.4. Screening and Selection Process

The selection of studies followed a multi-step process. First, in initial retrieval, approximately 450 articles were retrieved from all databases. After removing duplicates, 395 articles remained. Then, irrelevant studies were excluded, resulting in 120 articles for full-text assessment. In the next step, studies were evaluated against the inclusion and exclusion criteria, yielding 54 articles for the final review. Finally, the selected studies were categorized according to application domains, namely, smart grids, peer-to-peer (P2P) energy markets, intelligent transportation management, IoT-enabled urban services, and data security.

2.5. Data Extraction and Comparative Analysis

For each selected study, key information was systematically extracted, including publication year, application domain, AI techniques employed (e.g., machine learning, deep neural networks, reinforcement learning), blockchain platforms or consensus mechanisms, performance evaluation metrics, and major findings. Extracted data were organized into tables and comparative analyses were conducted to synthesize approaches and identify prevailing research trends.

2.6. Analytical Approach

The analysis combined both descriptive and analytical perspectives:

1. Descriptive analysis: Examined temporal publication trends and distribution across application domains.
2. Analytical review: Identified strengths and limitations of various approaches, key challenges highlighted in the literature, and emerging opportunities for advancing the integration of AI and blockchain in power systems and smart city infrastructures.

2.7. Research Limitations

Several limitations should be acknowledged: only articles published in English were included, which may overlook relevant studies in other languages. Access limitations prevented the inclusion of some full-text articles. Despite efforts for comprehensive coverage, some studies might have been missed due to database or keyword limitations. The focus on peer-reviewed publications may exclude recent industrial applications or gray literature that could provide practical insights.

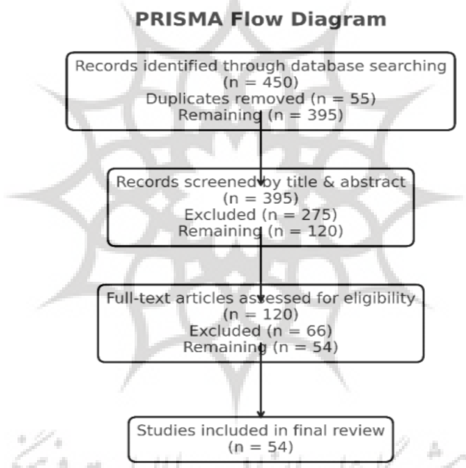

Figure 3. PRISMA Flow Diagram of the Methodology

3. Key Technologies

3.1 Artificial Intelligence

Artificial intelligence (AI), as one of the most advanced emerging technologies, plays a critical role in managing and optimizing energy systems and urban infrastructures. AI possesses the capability to process vast amounts of data and extract complex patterns, enabling intelligent decision-making and accurate forecasting across various energy and urban management domains (Li et al., 2023; Zekić-Sušac et al., 2021). One primary application of AI in smart cities is energy demand and load forecasting. For instance, by analyzing historical energy consumption data along with environmental factors, machine learning models, deep learning techniques, and neural networks can predict consumption patterns with high accuracy. Such predictions contribute to reducing energy waste and improving grid efficiency (Zekić-Sušac et al., 2021).

In the field of energy production and distribution, intelligent algorithms dynamically manage energy allocation to minimize losses and enhance responsiveness to variable consumer demand (Li et al., 2023). AI also plays a significant role in intelligent transportation system management. Real-time traffic data analysis allows for optimized traffic flow, reduced waiting times at intersections, and decreased congestion and pollution (Garg et al., 2024). Moreover, AI can process data collected from IoT sensors and devices to support urban decision-making in energy consumption, public services, and infrastructure management (Al-Fuqaha et al., 2015). The outcomes of these applications include increased efficiency, cost reduction, and improved urban quality of life.

Overall, AI provides data-driven, intelligent solutions and serves as a powerful tool for transforming energy systems and smart cities, significantly enhancing performance, sustainability, and urban well-being (Lukić et al., 2025; Moghaddam et al., 2022).

3.2. Blockchain

Blockchain, as a distributed ledger technology, enables the recording and management of transactions without intermediaries, thereby enhancing security and transparency while fostering trust between energy producers and consumers (Sahoo et al., 2025; Zhao et al., 2023). A key technical aspect of blockchain in smart cities is the consensus mechanism. Algorithms such as Proof of Work (PoW) and Proof of Stake (PoS) validate transactions and ensure data security within energy networks (Dorri et al., 2016).

Smart contracts further enable the automation of energy transactions, enhancing both accuracy and processing speed (Kodali et al., 2018). A practical example is the Brooklyn Microgrid, which allows direct peer-to-peer solar energy exchange, with all transactions recorded transparently and immutably on the blockchain (Mengelkamp et al., 2018).

In addition, secure storage of sensor data and urban system information enhances transparency and builds citizen trust (Miloud Dahmane et al., 2023; Paula Jr. et al., 2025). Designing a smart urban system architecture that integrates energy networks, microgrids, and IoT infrastructure with blockchain ensures security, scalability, and real-time data processing (Ahmed et al., 2022; Al Shareef et al., 2024).

Overall, blockchain provides a secure, transparent, and smart-contract-enabled infrastructure for the efficient and reliable management of urban data and energy transactions (Andoni et al., 2019; Hua et al., 2022; Khan et al., 2023).

4. Combined Applications of AI and Blockchain in Power Systems and Smart Cities

The integration of AI and blockchain technologies holds significant promise for the transformation of power systems and smart city infrastructures. AI empowers systems with capabilities such as demand forecasting, energy management, traffic prediction, and IoT data analytics, enabling better operational efficiency and reliability (Ahmed et al., 2022; AT et al., 2024). At the same time, blockchain offers decentralized, transparent, and immutable ledgers that enhance trust and security, facilitating smart contracts, secure energy trading, and reliable IoT data handling (Dorri et al., 2016).

When these technologies converge, their synergy can reshape domains such as renewable energy and urban services. For instance, in microgrids and peer-to-peer energy trading networks, AI-driven load and production forecasts optimize energy distribution, while blockchain ensures transaction transparency and automates settlements (Andoni et al., 2019). This process is illustrated in Figure 4, indicating how AI supports forecasting and blockchain guarantees secure transactions within a microgrid. Moreover, recent advancements emphasize edge AI for decentralized energy systems, such as federated learning and distributed control architectures, that can be integrated with blockchain to maintain security and enhance scalability, particularly in virtual power plant models and smart grids (Caganova et al., 2025; de Paula Jr et al., 2025; Sahoo et al., 2025).

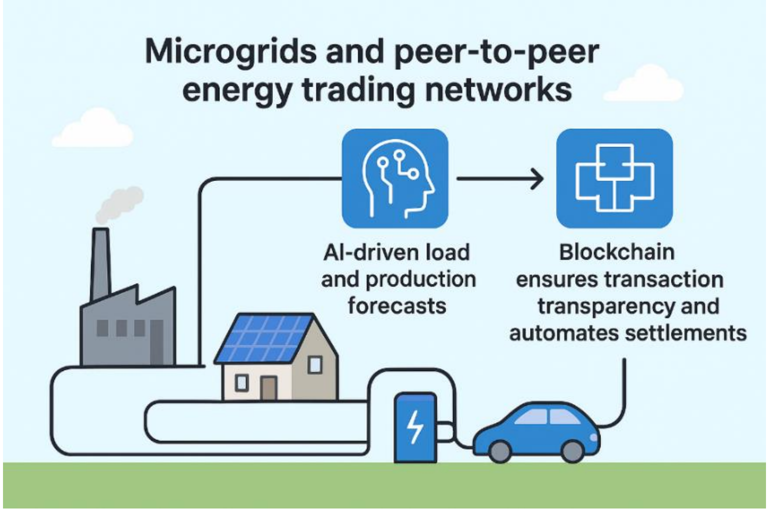

Figure 4. Integration of AI and Blockchain in Microgrids and Peer-to-Peer Energy Trading

The convergence of AI and blockchain offers significant potential to transform energy systems and urban infrastructures (Badidi, 2022; Caganova & Das, 2025). Primary applications and advantages are:

1. Energy Networks and Microgrid Optimization:
   - AI predicts load and energy production while planning distribution and management.
   - Blockchain ensures secure and transparent transactions and executes smart contracts (Al-Fuqaha et al., 2015; Mengelkamp et al., 2018).
2. Edge AI and Distributed Learning:
   - Federated learning and distributed control architectures enable decentralized energy systems.
   - Integration with blockchain enhances security and scalability in virtual power networks and smart grids (Badidi, 2022; Paula Jr. et al., 2025).
3. Support for Smart Urban Services:
   - AI and blockchain systems optimize urban services such as water, waste, parking, and intelligent transportation.
   - Outcome: improved transparency, trust, and service efficiency for citizens (Jeyaraj et al., 2025; Saidu et al., 2025).

Through such combined applications, AI and blockchain not only boost performance but also foster resilient, transparent, and trusted infrastructures. This integrated approach lays the foundation for more efficient, sustainable, and citizen-centric energy and urban service systems.

Table 1. Key Roles of AI and Blockchain Across Application Domains in Power Systems and Smart Cities

Application Domain	AI Role	Blockchain Role	Examples
Smart power grid	Load forecasting, production and distribution optimization	Energy transaction recording, smart contracts	Microgrids with autonomous energy management
Renewable energy management	Solar and wind production forecasting	Transparent energy sales	Peer-to-peer energy trading in smart homes
Intelligent transportation	Traffic prediction, vehicle scheduling	Travel data recording, electronic payments	Ride-sharing and smart transit systems
Urban services	IoT data analysis for decision-making	IoT data security, reporting	Water, waste, and parking management

5. Challenges and Opportunities

5.1. Challenges

Implementing combined artificial intelligence (AI) and blockchain systems in smart cities faces a set of technical, social, and organizational challenges. Analyzing these challenges through the blockchain triad framework (decentralization, security, and scalability) and the role of AI provides a clearer picture of inherent trade-offs in system design:

1. Technology Integration Complexity (Decentralization and Integration): Coordinating AI algorithms with blockchain architecture requires complex designs, protocol standardization, and alignment across decentralized systems. This is particularly critical in distributed energy networks and urban infrastructures (Ifedayo et al., 2025; Jain et al., 2024).
2. High Energy Consumption (Security and Sustainability): Consensus mechanisms such as Proof of Work (PoW) are energy-intensive, which may conflict with sustainable city goals, particularly in smart grids where energy efficiency is vital (Khan et al., 2023; Kodali et al., 2018).
3. Data Privacy and Security (Security): Storing sensitive urban and energy data on blockchain demands robust security protocols, advanced encryption, and legal compliance (Alrashdi et al., 2024; Dorri et al., 2016; Jain et al., 2024).
4. Implementation and Maintenance Costs (Decentralization and Operational Challenges): Deploying and maintaining AI-blockchain systems requires significant investment, specialized personnel, and advanced technological infrastructure (Far et al., 2024; Moghaddam et al., 2022).
5. Scalability Limitations (Scalability): Increasing transaction volumes and data may reduce blockchain performance, necessitating optimized distributed networks, Edge AI, and federated learning approaches (Dritsas & Trigka, 2024; Jeyaraj et al., 2025).
6. Regulatory and Standardization Challenges (Security and Regulation): Legal frameworks for energy data and smart contracts remain underdeveloped in many regions, limiting widespread adoption (Khan et al., 2023; Sahoo et al., 2025).
7. Social and Cultural Acceptance (Decentralization and Trust): Stakeholders and citizens may be hesitant to trust new technologies, requiring education, awareness campaigns, and transparency mechanisms (Al-Fuqaha et al., 2015; Far et al., 2024; Jain et al., 2024;).

5.2. Opportunities

Despite these challenges, the convergence of AI and blockchain offers substantial opportunities to enhance energy systems and urban services:

1. Enhanced Network Efficiency and Energy Savings (Decentralization and AI Optimization): AI and blockchain can optimize energy generation and consumption, reduce losses, and lower operational costs (Li et al., 2023; Salama et al., 2024).
2. Transparency and Trust (Security and Trust): Smart contracts and immutable transactions reduce fraud and data risks, increasing stakeholder confidence (Gupta et al., 2024; Zhao et al., 2023).
3. Sustainable Energy Management (Sustainability and Decentralization): Facilitating renewable energy utilization and secure peer-to-peer (P2P) energy trading supports the development of green urban networks (Mengelkamp et al., 2018; Purushothaman et al., 2024).

4. Improved Urban Decision-Making (AI and Secure Data Analytics): AI-driven data analytics combined with secure blockchain storage enables rapid, data-driven, and adaptive urban planning (Ahmed et al., 2022; Hamza et al., 2021).
5. Development of Novel Urban Services (Decentralization and AI Services): Smart payments, resource sharing, waste management, and optimized transportation provide opportunities for innovative urban service offerings (AT et al., 2024; Garg et al., 2024).
6. Business Model Innovation (Decentralization and P2P Markets): P2P energy markets and digital urban services allow the creation of novel and flexible business models (Caganova & Das, 2025; Khanna et al., 2021).
7. Operational Cost Reduction (Operational Efficiency and Decentralization): Minimizing intermediaries and optimizing processes reduces municipal costs and enhances operational efficiency (Gupta et al., 2024; Salama et al., 2024).

Table 2. Analysis of Challenges and Opportunities through Blockchain Triad and AI Roles

Category	Challenges	Opportunities	Blockchain Dimension	Role of AI	References
Technology Integration Complexity	Coordinating AI algorithms with blockchain architecture and protocol standardization	Enhancing system interoperability and increasing network flexibility	Decentralization	Optimization algorithms and data coordination	Ifedayo et al. (2025); Jain et al. (2024)
High Energy Consumption	Energy-intensive consensus mechanisms such as PoW	Implementing low-energy algorithms and integrating renewable energy sources	Security and Sustainability	Load forecasting and intelligent energy management	Khan et al. (2023); Kodali et al. (2018)
Data Privacy and Security	Storing sensitive data requires strict security protocols and compliance	Increasing stakeholder trust and data security	Security	Encryption and predictive threat analysis	Alrashdi et al. (2024); Jain et al. (2024); Dorri et al. (2016)
Implementation and Maintenance Costs	High initial investment and need for specialized personnel	Long-term cost reduction via automation and smart contracts	Decentralization	Resource and process automation	Far et al. (2024); Moghaddam et al. (2022)
Scalability Limitations	Increased transaction volumes may degrade network performance	Developing distributed networks and improving performance	Scalability	Load management algorithms and big data analytics	Jeyaraj et al. (2025); Dritsas & Trigka (2024)
Regulatory and Standardization Challenges	Lack of legal frameworks for energy data and smart contracts	Establishing global standards and regulatory transparency	Security and Regulation	Data analysis for compliance with policies and regulations	Khan et al. (2023); Sahoo et al. (2025)
Social and Cultural Acceptance	Stakeholders hesitant to adopt new technologies	Education and awareness campaigns to improve adoption	Decentralization and Trust	AI tools for transparent decision explanation and social behavior prediction	Far et al. (2024); Jain et al. (2024); Al-Fuqaha et al. (2015)

6. Comparative Review of Prior Studies and the Novelty of the Present Article

6.1. Overview of the Literature

Research on the integration of artificial intelligence (AI) and blockchain in the context of smart cities has grown rapidly in recent years. Earlier studies tended to investigate these technologies separately. For instance, blockchain was primarily examined in the context of decentralized energy trading and trust mechanisms (Andoni et al., 2019; Mengelkamp et al., 2018; Zhao et al., 2023). Similarly, machine learning and deep learning approaches were employed to improve forecasting, resilience, and efficiency in energy systems (Li et al., 2023; Song et al., 2022; Zekić-Sušac et al., 2021).

More recently, the literature has begun to explore the synergies between AI and blockchain, recognizing their complementary potential. Khan et al. (2023) emphasized security improvements in grid management, while Hua et al. (2022) and Jeyaraj et al. (2025) examined prosumer energy markets and energy efficiency strategies. However, these studies often remained narrowly focused on the energy sector, limiting the broader implications for urban systems. Similarly, Sahoo et al. (2025), Al Shareef et al. (2024), and Sharma et al. (2021) discussed AI–blockchain integration for smart cities, but largely from a conceptual or policy-oriented perspective.

In parallel, emerging studies have highlighted cross-sectoral applications, such as green economy transitions (Caganova & Das, 2025), IoT data integrity (Garg et al., 2024; Miloud Dahmane et al., 2023), and AI explainability in smart cities (Javed et al., 2023). Nevertheless, these contributions often lack empirical validation or remain confined to a single technological or sectoral dimension.

Recent state-of-the-art studies underscore the need for integrative and interdisciplinary approaches. Al Jasem et al. (2025) conducted a systematic review of AI–blockchain convergence for decentralized intelligent systems, including sustainable urban infrastructure, emphasizing the importance of scalability. Idrissi et al. (2024) demonstrated blockchain-enabled AI applications in mobility and traffic optimization. Merrad et al. (2022) highlighted that how combining blockchain with machine learning can enhance the resilience of smart energy grids.

Taken together, the literature suggests three major gaps: (i) limited cross-domain analysis beyond energy systems, (ii) insufficient empirical frameworks to operationalize AI–blockchain integration, and (iii) overreliance on conceptual models. The present article aims to position itself modestly within this evolving body of work by offering a comparative synthesis and a structured, practice-oriented framework that addresses energy networks, renewable markets, transport, and IoT-enabled services simultaneously.

6.2. Comparative Analytical Table (28 Key Studies)

Table3. Comparative Review of Selected Studies

Author(s)/Year	Scope	Methodology	Key Findings	Limitations	Type of Study/Data
Andoni et al. (2019)	Blockchain in decentralized energy	Systematic review	Identified opportunities and barriers in P2P energy trading	Lacks AI dimension	Conceptual
Zekić-Sušac et al. (2021)	Energy forecasting with ML	Applied ML model	Demonstrated efficiency gains through predictive analytics	Ignores blockchain and security issues	Simulation

Li et al. (2023)	Deep learning for smart grids	Empirical modeling	Achieved high predictive accuracy	No transparency or security mechanisms	Emprical
Garg et al. (2024)	AI in smart homes/buildings	Simulation-based study	Practical focus on energy savings	Excludes blockchain aspects	Simulation
Badidi (2022)	Edge AI & blockchain in smart cities	Conceptual model	Emphasized role of edge computing	Narrow scope, lacks cross-domain model	Conceptual
Khan et al. (2023)	AI–blockchain for grid security	Conceptual framework	Highlighted blockchain for cyber-resilience	Remains mostly theoretical	Conceptual
Hua et al. (2022)	AI–blockchain for energy prosumers	Applied modeling	Provided comprehensive sectoral analysis	Restricted to energy only	Simulation
Sahoo et al. (2025)	Blockchain in smart cities	Policy-oriented review	Addressed governance and regulatory aspects	Limited AI analysis	Conceptual
Caganova & Das (2025)	AI–blockchain for green economy	Conceptual study	Linked sustainability with digital innovation	Lacks detailed energy analysis	Conceptual
Al Shareef et al. (2024)	AI–blockchain in energy systems	Systematic review	Rigorous synthesis of methods in energy	Narrow focus on energy	Review
Mengelkamp et al. (2018)	Brooklyn Microgrid (blockchain)	Real-world pilot	Demonstrated blockchain-based P2P trading	Excludes AI dimension	Emprical
Miloud Dahmane et al. (2023)	blockchain for urban data integrity	Conceptual study	Addressed trust and security in data	No AI-driven optimization	Conceptual
Lukić et al. (2025)	AI–blockchain–digital Twin framework	Applied model	Explored synergies of three emerging technologies	Case-specific, lacks generalizability	Simulation
Ahmed et al. (2022)	AI–blockchain in IoT	Conceptual model	Proposed integration for IoT environments	Lacks empirical validation	Conceptual
Dorri et al. (2016)	blockchain in IoT	Exploratory	Early identification of IoT challenges	Outdated, no AI	Conceptual
Ifedayo et al. (2025)	Review of AI–blockchain convergence	Systematic review	Future-oriented insights	No applied framework	Review
Jeyaraj et al. (2025)	Energy management with AI–Blockchain	Applied approach	Improved energy efficiency through integration	Limited to energy domain	Simulation
Dritsas & Trigka (2024)	ML for IoT–blockchain in cities	Technical study	Showed synergies for IoT–blockchain	Lacks practical use cases	Simulation
Zhao et al. (2023)	blockchain in smart grids	Umbrella review	Strong methodological synthesis	Ignores AI	Review
Lobus et al. (2023)	Carbon reduction with digital tech	Conceptual	Addressed sustainability using digital tools	No AI–blockchain integration	Conceptual
Javed et al. (2023)	Explainable AI in smart cities	Applied AI model	Enhanced transparency in decision-making	Excludes blockchain	Simulation
Sharma et al. (2021)	AI–blockchain for sustainable cities	Conceptual framework	Proposed governance-oriented model	Insufficient sectoral depth	Conceptual
Mololoth et al. (2023)	Blockchain + ML for energy futures	Empirical modeling	Highlighted role in energy transition	Focused only on energy	Emprical
Saidu et al. (2025)	AI–blockchain–IoT for traceability	Applied model	Strengthened supply chain transparency	Narrow traceability domain	Simulation

Song et al. (2022)	Resilience of smart power grids	Empirical study	Demonstrated AI-based resilience	Lacks blockchain	Emprical
Al Jasem et al. (2025)	AI–blockchain for decentralized intelligent systems including urban infrastructure	Systematic review	Identified integration opportunities for sustainability	Limited to conceptual synthesis	Review
Idrissi et al. (2024)	Blockchain-enabled AI in mobility	Systematic review-based synthesis	Improved traffic optimization and smart mobility	Focused on transport only	Review
Merrad et al. (2022)	Blockchain + ML for energy resilience	Applied study	Enhanced reliability of smart grids	Domain-limited to energy	Simulation

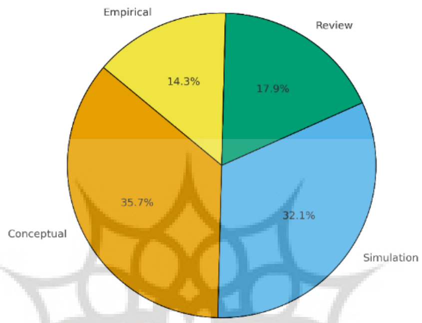

Figure 5. Distribution of Study Types in Comparative Review

The pie chart illustrates the distribution of study types (conceptual, simulation, empirical, and review) in the comparative analysis. The results indicate that the majority of the reviewed studies fall into the conceptual category, reflecting a strong emphasis on theoretical frameworks and model development. Simulation-based studies constitute the second-largest group, highlighting the role of controlled environments in testing innovative approaches. In contrast, empirical studies account for a smaller proportion, suggesting that real-world, data-driven validations remain relatively limited. Finally, review studies represent a distinct category, focusing primarily on synthesizing existing knowledge and identifying future research directions.

Synthesis of the Comparative Analysis

The comparative analysis highlights that the literature has evolved from single-technology applications (AI-only or blockchain-only) toward initial explorations of combined frameworks. However, most contributions remain either narrowly focused on the energy sector, conceptually driven, or lacking empirical validation across multiple urban domains.

The present article positions itself as a modest but integrative contribution. Instead of claiming to resolve all identified gaps, it synthesizes previous findings and proposes a cross-sectoral framework that connects energy networks, renewable markets, transport, and IoT-enabled services. By combining insights from both AI and blockchain literatures, this article aspires to provide a more holistic yet practical orientation, laying the groundwork for subsequent empirical research and policy-oriented applications.

6.3 Concluding Analytical Remarks

The comparative review indicates that while prior literature offers valuable insights, it is largely fragmented and domain-specific, with few studies providing empirical evidence. The originality of the present article lies in:

1. Offering a cross-sectoral synthesis connecting energy, transport, IoT services, and renewable markets.
2. Quantifying the types of studies and highlighting gaps in operational data.
3. Proposing an integrative framework that consolidates dispersed research strands, serving as a foundation for future empirical or simulation-based studies.

7. Proposed Roadmap for Integrating AI and Blockchain in Power Systems and Smart Cities

The development and implementation of AI and blockchain technologies in power systems and smart cities can be illustrated over three time horizons: short-term (2025–2030), medium-term (2030–2040), and long-term (2040–2050). These periods reflect the different stages of technological maturity and evolution.

1. Short-Term Horizon (2025–2030)

❖ Primary Focus: Establishing infrastructure and pilot testing

1. Development of AI algorithms for energy consumption forecasting and load management in smart grids.
2. Limited deployment of blockchain for energy transaction recording and enhancing transparency in pilot systems.
3. Initiation of pilot projects for smart microgrids with peer-to-peer (P2P) energy trading capabilities.
4. Integration of AI in intelligent transportation: traffic prediction, public transport scheduling.
5. Early research on cybersecurity challenges and initial standards for smart contracts.

2. Medium-Term Horizon (2030–2040)

❖ Primary Focus: Integration and expansion

1. Deployment of commercial and industrial microgrids at the city level, using AI for prediction and optimization and blockchain for smart contracts.
2. Integration of AI and blockchain in intelligent transportation:
    - Secure electronic payments
    - Smart management of electric fleets
3. Establishment of blockchain-based renewable energy markets involving consumer participation (prosumers).
4. Standardization of smart contracts in energy and urban services.
5. Development of interoperable protocols connecting AI, blockchain, and IoT for smart cities.
6. Initiation of federated learning approaches to manage energy data and reduce reliance on centralized processing.

3. Long-Term Horizon (2040–2050)

❖ Primary Focus: Full maturity and sustainability

1. Full implementation of Virtual Power Plants (VPPs) managed by AI and blockchain.
2. Development of distributed control systems for national and regional smart grids.

3. Autonomous AI for comprehensive urban energy optimization, with blockchain for immutable data recording.
4. Integration of multiple urban sectors (energy, water, transportation, waste management) under a unified AI + blockchain platform.
5. Expansion of sustainable smart cities, where AI and blockchain form the backbone of resource and service management.
6. Establishment of international standards for coordinated and legal use of smart contracts at the global level.

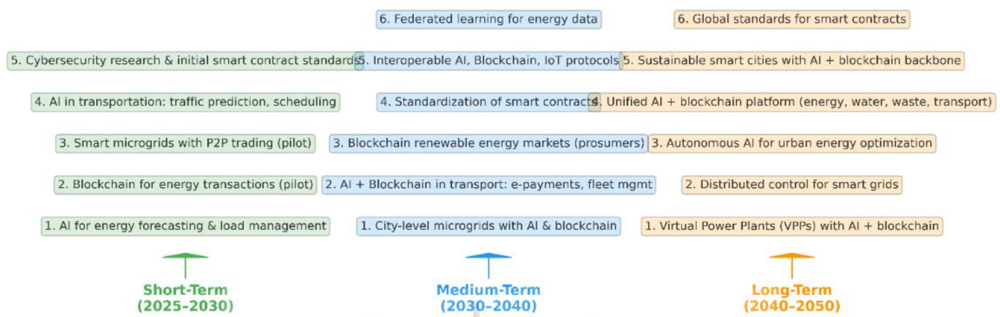

Figure 6. Roadmap for AI and Blockchain Integration in Power Systems and Smart Cities (2025–2050)

8. Conclusion

The convergence of AI and blockchain represents one of the most significant directions for transforming energy systems and smart city infrastructures. Together, these technologies have the potential to fundamentally reshape the way energy is produced, distributed, and consumed, while also enhancing the efficiency of urban services. AI, with its capacity for big data analytics, demand forecasting, network optimization, and IoT-based data processing, provides the foundation for intelligent decision-making and improved efficiency. In parallel, blockchain through decentralization, transparency, immutability, and smart contract automation offers a secure infrastructure for data exchange and the management of complex transactions. Their integration paves the way for sustainable energy networks, more efficient urban services, and reliable transportation systems. The impacts, opportunities, and challenges of this integration across smart city domains are systematically summarized in Table 4.

The distinct contribution of this study compared to prior research lies in presenting an integrated and analytical framework that highlights the interplay between AI functionalities and blockchain capabilities. Whereas much of the earlier literature has discussed these technologies in isolation, this systematic review demonstrates how their synergies can generate innovative solutions in energy management, transportation, and urban services. Furthermore, by consolidating existing evidence and critically identifying knowledge gaps, the study not only clarifies the current state of research but also highlights pathways for future investigation and policymaking.

Despite these contributions, certain limitations must be acknowledged. The review is based on 54 selected sources, implying that very recent studies or unpublished industrial reports may not have been captured. Moreover, methodological heterogeneity among the reviewed works, ranging from simulations and small-scale pilots to case studies, limits the ability to directly compare findings or extract consistent quantitative indicators. Many of the studies remain conceptual or confined to limited pilots, leaving insufficient evidence regarding large-scale implementation, real costs, or long-term environmental impacts. Blockchain's high energy consumption is often reported through theoretical estimations rather than empirical evaluations across different architectures in real-world conditions. Finally, language and access constraints may have excluded some non-English or grey literature, and publication bias could have influenced the available evidence.

These limitations underscore the need for further research. Developing energy-efficient blockchain architectures and AI algorithms optimized for resource-constrained environments will be crucial to overcoming technical barriers. Equally important are the standardization of smart contracts and interoperable protocols to support collaboration among diverse stakeholders. Beyond technical considerations, regulatory sandboxes and transparent communication of benefits and risks will be key to fostering social acceptance. Real-world pilot projects, accompanied by open publication of their data and outcomes, can enable more rigorous evaluation and comparability across studies.

In sum, this systematic review demonstrates that the integration of AI and blockchain holds great promise for improving efficiency, security, and sustainability in energy systems and urban services. Yet, realizing this vision requires addressing technical, organizational, and socio-legal challenges simultaneously. By leveraging emerging opportunities and responding to these barriers, AI–blockchain convergence can serve as a foundation for transparent, resilient, and citizen-centric smart cities of the future.

Table 4. Summarizes the Combined Impact of AI and Blockchain in Smart Cities

Application Domain	Benefits	Challenges	Opportunities
Smart power grid	Optimized load and distribution, demand forecasting	High energy consumption, limited scalability	Reduced energy waste, sustainable management
Renewable energy	Production forecasting, surplus energy sales	Unclear regulations, implementation costs	P2P energy markets, transaction transparency
Intelligent transportation	Traffic reduction, vehicle scheduling	Social acceptance, system complexity	Novel urban services, improved decision-making
Urban services	IoT data analysis, resource management	Data security, standardization	Cost reduction, enhanced service quality

Integrating AI and blockchain presents a transformative pathway toward smarter, safer, and more sustainable urban environments. By addressing technical, regulatory, and social challenges, cities can harness these technologies to meet future energy and service demands efficiently.

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