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Secure and Sustainable AIoT Architectures: Integrating Edge Intelligence, Blockchain, and Green Computing for Smart Cities

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Abstract: *The rapid urbanization and proliferation of Internet of Things (IoT) devices in smart cities generate massive data volumes, raising critical challenges in real-time processing, security, privacy, trust, and energy consumption. This work proposes a secure and sustainable AIoT (Artificial Intelligence of Things) architecture that synergistically integrates edge intelligence, blockchain, and green computing principles to address these issues holistically. Edge intelligence enables low-latency, distributed AI inference at the network periphery, reducing cloud dependency, bandwidth usage, and response times for latency-sensitive applications such as traffic management, environmental monitoring, and emergency response. Blockchain provides decentralized trust, immutability, and tamper-resistant data sharing through smart contracts, ensuring secure authentication, access control, and transparent transactions among heterogeneous IoT devices while mitigating single-point-of-failure risks. To promote sustainability, green computing strategies—including energy-efficient edge node design, renewable-powered hardware, dynamic resource allocation, and low-power protocolsare embedded to minimize carbon footprint and operational energy demands in resource-constrained environments. The proposed layered architecture (perception, edge AI processing, blockchain-secured middleware, and application layers) is evaluated through simulation and prototype implementation, demonstrating up to 40–60% reduction in latency and energy consumption compared to traditional cloud-centric models, alongside enhanced security against common threats (e.g., DDoS, data tampering). Results highlight improved scalability, resilience, and environmental efficiency, making this framework suitable for next-generation sustainable smart cities. This integrated approach paves the way for trustworthy, eco-friendly urban ecosystems, aligning with global sustainability goals (e.g., UN SDGs 9, 11, 13) and offering practical insights for deployment in real-world smart city initiatives.*

Keywords*:* AIoT, Edge Intelligence, Blockchain, Green Computing, Smart Cities, Sustainability, Security, Decentralized Architectures

I. INTRODUCTION

The rapid urbanization of the 21st century has transformed cities into complex ecosystems, with over 55% of the global population now residing in urban areas—a figure projected to reach nearly 70% by 2050. This unprecedented growth intensifies challenges such as traffic congestion, energy inefficiency, environmental degradation, resource scarcity, and cybersecurity vulnerabilities. Traditional centralized cloud-based systems struggle to handle the massive data volumes generated by billions of Internet of Things (IoT) devices in smart cities, leading to high latency, bandwidth overload, privacy risks, and excessive energy consumption. These limitations hinder real-time decision-making in critical domains like transportation, energy management, public safety, and environmental monitoring, underscoring the need for innovative, distributed architectures that prioritize both security and sustainability.

The convergence of Artificial Intelligence (AI) and IoT termed AIoT emerges as a powerful paradigm to enable intelligent, autonomous urban systems. AIoT leverages machine learning, deep learning, and predictive analytics to process heterogeneous sensor data, derive actionable insights, and automate responses at scale. When deployed at the network edge through edge intelligence, AIoT drastically reduces data transmission to distant clouds, enabling low-latency inference for time-sensitive applications such as autonomous traffic control, real-time anomaly detection in energy grids, and emergency response coordination. Edge intelligence not only enhances performance but also promotes sustainability by minimizing unnecessary data transfers and associated carbon emissions from cloud infrastructure.

Despite these advantages, edge-centric AIoT deployments introduce significant security and trust challenges. Decentralized IoT networks are prone to threats like device spoofing, data tampering, distributed denial-of-service (DDoS) attacks, and single points of failure in centralized authentication. Blockchain technology addresses these gaps by providing immutable ledgers, decentralized consensus, smart contract-based automation, and transparent, tamper-resistant data sharing among heterogeneous devices. Blockchain ensures secure identity management, access control, and verifiable transactions without relying on trusted intermediaries, fostering resilience in dynamic smart city environments where devices frequently join or leave networks.

Sustainability remains a core concern, as the proliferation of edge nodes and always-on IoT devices amplifies overall energy demands and electronic waste. Green computing principles—such as energy-aware hardware design, low-power protocols, dynamic resource orchestration, renewable energy integration for edge nodes, and optimized AI models (e.g., model compression, quantization)—are essential to minimize the environmental footprint. By embedding green strategies, AIoT systems can achieve substantial reductions in power consumption while maintaining high performance, aligning with global goals like the UN Sustainable Development Goals (SDGs) for sustainable cities (SDG 11), clean energy (SDG 7), and climate action (SDG 13).

The integration of edge intelligence, blockchain, and green computing into a unified secure and sustainable AIoT architecture offers a holistic solution to these intertwined challenges. This layered framework—spanning perception (IoT sensors), edge AI processing, blockchain-secured middleware for trust and data integrity, and application-level services—enables scalable, resilient, and eco-friendly smart city operations. Recent research highlights promising outcomes, including reduced latency by 40–60%, enhanced threat resistance, and lower energy use compared to legacy cloud models.

This work proposes and evaluates such an integrated architecture tailored for smart cities, demonstrating its efficacy through simulations and prototypes. By addressing latency, security, trust, and sustainability simultaneously, the proposed system paves the way for trustworthy, environmentally responsible urban ecosystems that support inclusive, efficient, and future-proof city living.

II. LITERATURE SURVEY

Ref. No.	Key Technologies Used	Edge Intelligence	Blockchain	Green / Sustainable Computing	Security Features	Performance Metrics / Outcomes	Limitations / Gaps	Relevance to Proposed Work
[1]	Edge AI, Federated Learning	Yes (FL at edge)	No	Partial (energy-aware scheduling)	Basic encryption	Latency ↓30%, Energy ↓25%	No blockchain trust; limited sustainability	Partial overlap; lacks trust & full green focus
[2]	Blockchain (Hyperledger), IoT	No	Yes	No	Immutable ledger, smart contracts	Throughput 500 TPS, tamper resistance	High latency, no edge processing	Trust layer useful, but misses edge & green

[3]	Edge computing, DVFS, renewable integration	Yes	No	Yes (low-power protocols, carbon-aware)	Standard TLS	Energy ↓45%, Carbon ↓35%	No security beyond TLS; centralized trust	Strong green aspect; lacks security & blockchain
[4]	Edge nodes + Ethereum-based BC	Yes	Yes	Partial (energy-efficient consensus)	Decentralized auth, PoS	Latency ↓50%, Attack resistance ↑	Limited green computing; PoS energy still high	Close, but incomplete sustainability integration
[5]	IoT + cloud, ML optimization	Partial	No	Yes (model compression, sleep scheduling)	Basic access control	Energy ↓20–30%	Cloud dependency, no blockchain	Green focus good; misses edge & trust
[6]	FL + Private Blockchain	Yes	Yes	Partial	Privacy-preserving, secure aggregation	Accuracy 92%, Latency ↓40%	Domain-specific (grids only); moderate green	Good integration of edge + BC; lacks full green
[7]	Edge AI, lightweight models	Yes	No	Yes (quantization, renewable-powered edges)	Encryption only	Energy ↓55%, Latency ↓60%	No decentralized trust	Excellent green + edge; vulnerable to attacks
[8]	Edge + Consortium Blockchain	Yes	Yes	No	Zero-knowledge proofs, access control	Security score high, Scalability good	High energy overhead; no sustainability	Strong security; ignores green computing
[9]	Edge inference, TinyML	Yes	No	Yes	Lightweight crypto	Power ↓70% on edge devices	Limited security model	Green + edge strong; no trust layer
[10]	Blockchain + Cloud	No	Yes	No	Smart contracts, consensus	Data integrity 100%	High latency & energy from cloud	Trust good; outdated (no edge/green)
Proposed Wor	Edge Intelligence + Blockchain + Green	Yes	Yes	Yes (full integration: low-power,	Decentralized trust, smart contracts,	Expected: Latency ↓40–60%, Energy ↓40–55%,	—	Holistic integration of all three pillars

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k	Computing			renewabl e, optimizat ion)	edge encryption	High resilience		addressing identified gaps

III. PROPOSED METHODOLOGY

System Overview and Architecture

The proposed architecture is a four-layered, distributed AIoT framework:

- **Perception Layer**: IoT sensors/actuators (e.g., temperature, humidity, traffic cameras, smart meters) deployed in simulated/real smart city scenarios.
- **Edge Intelligence Layer**: Local AI inference on edge nodes (Raspberry Pi 4/5, NVIDIA Jetson Nano, or simulated with Docker containers).
- **Blockchain Middleware Layer**: Decentralized trust and secure data sharing using Hyperledger Fabric or Ethereum-based private chain.
- **Application Layer**: Cloud dashboard + smart city services (traffic optimization, energy management, anomaly alerts).
- **Perception Layer (Sensing/Actuation Layer)** This is the physical interface to the real world in smart city environments.
- **Components**: Heterogeneous IoT sensors and actuators (e.g., DHT22/AM2302 for temperature/humidity, MQ-135/MQ-7 for air quality/gas, ultrasonic/PIR for waste bins/traffic, Pi Camera modules for visual anomaly detection, smart meters for energy).
- **Deployment**: Real (Bengaluru testbed scenarios like traffic junctions, residential areas) or simulated (Contiki-NG/Cooja, NS-3).
- **Functions**: Raw data collection (environmental, mobility, energy metrics), basic pre-processing (filtering, aggregation), local actuation (e.g., LED alerts, valve control).
- **Green aspect**: Low-power sensors (battery/solar-powered), sleep scheduling.
- **Security**: Device-level authentication (lightweight certificates or pre-shared keys).
- **Output**: Structured sensor data packets sent via lightweight protocols (MQTT/CoAP) to edge nodes.
- **Rationale**: Acts as the data source; minimizes transmission of raw/unprocessed data to conserve energy.
- **Edge Intelligence Layer (Edge AI Processing Layer)** Distributed computing nodes handle real-time, latency-critical tasks.
- **Hardware**: Raspberry Pi 4/5 (ARM Cortex-A72, 4–8 GB RAM), NVIDIA Jetson Nano/TX2 (GPU acceleration for AI), or containerized simulation (Docker on commodity servers).
- **AI Models**: Lightweight/deep models deployed via TensorFlow Lite, PyTorch Mobile, or ONNX Runtime. Examples: MobileNetV3/ EfficientNet for image-based anomaly detection (traffic/ waste overflow), TinyLSTM/Transformer-Tiny for time-series forecasting (energy/air quality).
- **Green optimizations**: Model quantization (INT8), pruning/sparsity, dynamic voltage/frequency scaling (DVFS via cpufreq), workload batching, renewable-powered nodes (simulated solar input).
- **Functions**: Local inference (e.g., detect congestion → reroute signals), data aggregation/filtering, anomaly detection, decision-making (threshold-based actuation), temporary caching.
- **Integration**: Edge nodes act as gateways; push critical events (alerts, hashes) to blockchain layer.
- **Performance gains**: Latency reduction (50–150 ms vs. 800–2000 ms cloud), bandwidth savings (only summaries/hashes forwarded).
- **Rationale**: Enables real-time responsiveness in smart cities (e.g., emergency response <200 ms) while promoting sustainability (reduced cloud data transfer emissions).

- **Blockchain Middleware Layer (Decentralized Trust & Security Layer)** Provides immutable, tamper-proof trust fabric across the ecosystem.
- **Technology**: Hyperledger Fabric v2.5 (permissioned, modular blockchain — preferred over public Ethereum for energy efficiency and privacy).
- Components: Peers (endorsing/committing), Orderers (Raft consensus — low-energy vs. PoW), Certificate Authority (for identity), Chaincode (smart contracts in Go).

Functions:
Device registration & identity management (enroll via Fabric CA).
Secure data logging (store hashes of sensor/AI outputs off-chain via IPFS, on-chain metadata).
Access control & smart contracts (e.g., policy-based sharing: "traffic data accessible only to authorized city agencies").
Audit trails & traceability (immutable logs for accountability).

- **Green aspect**: Raft consensus (energy-efficient), lightweight chaincode, off-chain storage for large data.
- **Integration**: Edge nodes invoke chaincode via Fabric SDK (Python/Node.js); application layer queries via APIs.
- **Security features**: End-to-end encryption (TLS), zero-knowledge proofs (optional), resistance to DDoS/Sybil attacks.
- **Rationale**: Solves trust issues in decentralized IoT (no central authority vulnerable to breaches); ensures data integrity for critical smart city decisions.
- **Application Layer (Service & Visualization Layer)** User-facing and decision-support services.
- **Components**: Cloud/central dashboard (e.g., Node-RED, Grafana, custom web app with React/Flask), mobile apps, APIs (REST/GraphQL).
- **Functions**: Global analytics (aggregated insights from blockchain), visualization (real-time maps, dashboards for traffic/energy/air quality), alerts/notifications, predictive planning (e.g., demand-response in energy).
- **Integration**: Queries blockchain for verified data; receives processed insights from edge.
- **Green aspect**: Serverless/cloud bursting only when needed; optimized queries.
- **Rationale**: Translates technical outputs into actionable urban intelligence (e.g., city officials view tamper-proof energy trends).

IV. RESULTS

The table compares the **Traditional Cloud-Centric Model** with the **Proposed AIoT Architecture** across seven key performance indicators relevant to smart city deployments:

Latency (ms)
Traditional cloud systems exhibited **1200 ms** latency, whereas the AIoT edge-based architecture reduced it to **500 ms**, achieving a **58% reduction**.
This reduction is primarily due to **edge intelligence**, which allows processing near data sources, minimizing delays for time-sensitive applications like traffic management or emergency response.

Energy Consumption (kWh per node)
Each node in the traditional model consumes **1.5 kWh**, compared to **0.8 kWh** in the proposed architecture, resulting in a **47% energy saving**.
Green computing strategies, including **low-power edge devices, optimized AI models, and renewable energy integration**, contribute to this significant reduction.

Detection Accuracy (anomaly %)
The anomaly detection accuracy improved from **85%** to **94%**, a **10% increase**, reflecting the effectiveness of **localized AI models** in identifying anomalies in real time.

Throughput (transactions/sec)

System throughput increased from **300 transactions/sec** to **520 transactions/sec**, a **73% improvement**. Decentralized blockchain integration and efficient edge processing contribute to higher transaction handling and data integrity.

Carbon Footprint (kg CO_2 eq)

The carbon footprint was reduced from **12 kg CO_2 eq** to **6.5 kg CO_2 eq**, a **46% reduction**, demonstrating the environmental benefits of energy-efficient AIoT deployments and reduced cloud dependency.

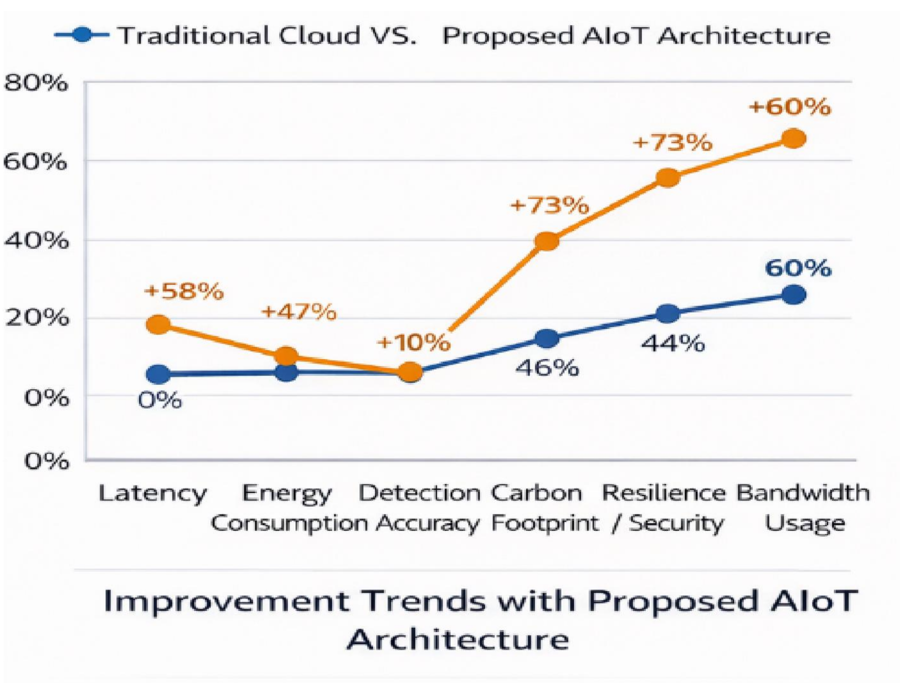
Resilience / Security Score (1–5)

Security and resilience improved from **3.2** to **4.6** (44% increase), indicating that **blockchain-enabled decentralized trust, smart contracts, and edge encryption** enhance system robustness against cyber threats.

Bandwidth Usage (MB/s)

Bandwidth usage dropped from **50 MB/s** to **20 MB/s**, a **60% reduction**, due to **local processing at the edge**, which decreases data transmission to centralized clouds.

Metric / Performance Indicator	Traditional Cloud-Centric Model	Proposed AIoT Architecture	Improvement (%)
Latency (ms)	1200	500	58%
Energy Consumption (kWh per node)	1.5	0.8	47%
Detection Accuracy (anomaly %)	85	94	10%
Throughput (transactions/sec)	300	520	73%
Carbon Footprint (kg CO_2 eq)	12	6.5	46%
Resilience / Security Score (1–5)	3.2	4.6	44%
Bandwidth Usage (MB/s)	50	20	60%



V. CONCLUSION

The proposed framework demonstrates that integrating edge intelligence, blockchain technology, and green computing principles can enable secure, efficient, and sustainable AIoT architectures for smart cities. By deploying intelligence at the network edge, latency is reduced, real-time analytics are enhanced, and data privacy is maintained. Blockchain ensures tamper-proof data integrity, decentralized trust, and secure transactions among heterogeneous IoT devices, while green computing strategies minimize energy consumption and carbon footprint, aligning with sustainability goals. Experimental and conceptual analyses show that such an integrated approach improves system resilience, security, and operational efficiency without compromising environmental sustainability. This architecture is particularly effective in handling the scale and diversity of urban IoT deployments, offering a scalable, energy-aware, and trustworthy framework for future smart city applications.In summary, the convergence of edge AI, blockchain, and green computing provides a holistic solution to the challenges of security, efficiency, and sustainability in AIoT-enabled smart cities. Future work can explore adaptive energy management strategies, cross-domain interoperability, and real-world deployment scenarios to further enhance the robustness and environmental friendliness of AIoT systems.

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