

AN INTERNET OF THINGS-BASED SMART CITY ARCHITECTURE MODEL FOR OPTIMIZING URBAN ENERGY MANAGEMENT

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ABSTRACT

This study proposes an Internet of Things (IoT) based smart city architecture to optimize urban energy management by integrating heterogeneous sensing, governed data harmonization, analytics-driven optimization, and dependable actuation in a closed-loop workflow. The research addresses a persistent urban challenge: energy-related data and controls are typically fragmented across utilities, municipal services, large buildings, and emerging mobility infrastructure, limiting citywide efficiency and peak-load mitigation. Guided by the theoretical lenses of IoT, Cyber-Physical Systems (CPS), and Demand Response (DR), the proposed architecture is structured into device/perception, interoperability and communication, semantic data management, analytics and optimization, and actuation/feedback layers, supported by cross-cutting security, privacy, and governance controls. The results indicate that the architecture strengthens cross-domain situational awareness, converts analytics into actionable and auditable decisions, and improves operational resilience through edge cloud partitioning and degraded-mode operation under imperfect data and connectivity. The study contributes a reference blueprint that links technical feasibility with institutional accountability, enabling scalable adoption and clearer evaluation of performance. Future work should emphasize longitudinal field validation, standardized metrics, and privacy-preserving optimization to enhance generalizability and readiness for deployment.



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INTRODUCTION

Urban energy systems are entering a period of structural change driven by rapid urbanization, electrification of transport and buildings, decentralization of generation, and increasingly volatile demand patterns. Cities are expected to deliver reliable, affordable, and low-carbon energy while also maintaining resilience against disturbances such as peak-load stress, extreme weather events, and infrastructure aging. At the same time, municipalities face mounting pressure to improve service quality and transparency, reduce operational losses, and align local energy planning with national and global sustainability targets (Mitra et al., 2025). These pressures make urban energy management a core pillar of smart city development, not merely a supporting utility. In practice, however, many cities still operate with fragmented monitoring, limited situational awareness, and reactive control strategies that cannot adequately cope with the scale and complexity of contemporary urban energy flows (Bai et al., 2025).

The Internet of Things (IoT) has emerged as a primary enabler for making energy systems observable, measurable, and controllable at granular levels. Smart meters, environmental sensors, intelligent street lighting, distributed energy resource (DER) controllers, building management systems, electric vehicle (EV) charging infrastructure, and microgrid components can collectively generate continuous streams of data about consumption, generation, power quality, occupancy, and contextual conditions (Esfandi & Byrne, 2026). When integrated into urban governance and utility operations, these data streams can support demand-side management, predictive maintenance, fault localization, dynamic pricing, and optimized dispatch of distributed resources. Yet the mere presence of IoT devices does not guarantee improved outcomes. Without a coherent architectural model, deployments often become isolated “islands” of sensing and automation, producing heterogeneous data that is difficult to integrate, validate, and use for reliable optimization across districts, sectors, and stakeholders (Alrawi & Al-Rawi, 2026).

Current state-of-the-art research and practice in smart energy cities typically combine IoT sensing with cloud-based analytics, machine learning for forecasting, and control strategies for demand response and DER coordination. Contemporary approaches increasingly incorporate edge computing to reduce latency, enhance reliability under network constraints, and support near-real-time actuation, especially for safety-critical functions such as voltage regulation or fault isolation. Digital twins and urban energy dashboards are also gaining prominence to provide operational visibility and scenario analysis for planners and operators (Šekarić-Stojanović, 2024). Despite these advances, several recurring limitations are evident. Interoperability remains a persistent challenge due to diverse vendors, protocols, and data formats, leading to costly integration and limited reuse across projects. Security and privacy concerns intensify as IoT extends into homes, buildings, and mobility systems, where fine-grained data can expose sensitive behavioral patterns. Many optimization frameworks assume ideal data quality and stable connectivity, whereas actual city environments include sensor drift, missing values, intermittent networks, and inconsistent metadata. Moreover, governance aspects such as accountability, data ownership, and cross-agency coordination are often treated as secondary considerations rather than explicit architectural elements (Em-Udom & Jaisumroum, 2023).

The main research problem addressed in this study is the absence of an integrated, scalable, and governance-aware IoT-based smart city architecture that can systematically optimize urban energy management across multiple domains and stakeholders. Existing solutions frequently focus on narrow use cases such as smart street lighting, smart metering, or building energy management without providing a unifying architectural blueprint that harmonizes data acquisition, semantic integration, analytics, and control. As a result, energy optimization efforts remain localized, limiting system-wide efficiency gains and complicating expansion to new districts or additional services. In addition, many architectures emphasize data collection and analytics but under-specify how optimization decisions are validated, deployed, monitored, and updated over time, particularly when the city's energy ecosystem evolves with new DERs, policy changes, and shifting demand patterns (Selvaraj et al., 2023).

This study identifies a research gap at the intersection of architecture design, operational optimization, and trustworthy data governance for urban energy management. First, there is a gap in architectural rigor: many proposed frameworks list components (devices, gateways, cloud) but do not formalize their interfaces, responsibilities, and data flows in a way that supports interoperability and lifecycle management. Second, there is a gap in cross-layer optimization: forecasting and optimization modules are often developed independently of data ingestion constraints, edge cloud partitioning, and actuation reliability, leading to solutions that perform well in controlled settings but degrade in operational contexts (Nozari & Tavakkoli-Moghaddam, 2026). Third, there is a gap in privacy and security by design: confidentiality and integrity are frequently appended as requirements rather than embedded as architectural primitives spanning identity, access control, encryption, auditability, and policy enforcement. Fourth, there is a gap in evaluation realism: performance is commonly measured using single datasets or simplified simulations that do not reflect multi-source heterogeneity, temporal drift, and the interaction between buildings, mobility, and distribution networks. These gaps motivate the need for an architectural model that is not only technically comprehensive but also implementable, measurable, and aligned with urban governance realities (Khemakhem et al., 2025).

Accordingly, the novelty of this research lies in proposing and substantiating an IoT-based smart city architectural model specifically tailored for urban energy management optimization, with explicit cross-layer coordination from sensing to actuation. The proposed model conceptualizes a modular multi-layer architecture that integrates device and field layers, edge intelligence, communication and interoperability services, a data management layer with semantic harmonization, and an application layer where forecasting, anomaly detection, and optimization are orchestrated as a closed-loop control system. The model emphasizes standardized interfaces and a unified energy data representation to reduce integration friction and support multi-vendor deployments. It also embeds security, privacy, and governance mechanisms such as fine-grained access policies, provenance tracking, and auditable decision logs into the core architectural flow, enabling trustworthy optimization in environments where data sensitivity and accountability are non-negotiable. By treating resilience and operational constraints as first-class architectural concerns, the model aims to remain effective under imperfect data and connectivity, which is characteristic of real-world urban settings (Zhu & Yue, 2025).

Guided by these contributions, this study asks the following research questions: How can an IoT-based smart city architecture be designed to integrate heterogeneous energy-related data sources and stakeholders while remaining scalable and interoperable? How should analytics and optimization functions be partitioned across edge and cloud resources to balance latency, reliability, and computational efficiency? What governance, security, and privacy mechanisms are necessary to ensure that optimization decisions are trustworthy, auditable, and compliant with policy constraints? To what extent can the proposed architecture improve measurable outcomes in urban energy management such as peak load reduction, operational efficiency, fault response time, and energy loss minimization under realistic conditions of data noise and network variability? These questions connect architectural design to operational performance and institutional feasibility, reflecting the multidisciplinary nature of smart city energy systems (S. et al., 2025).

The objectives of this research are to develop a reference architectural model for IoT-enabled smart city energy optimization; to define key components, interfaces, and data flows that support end-to-end observability and control; to specify an interoperable data management approach that enables semantic consistency across devices, buildings, mobility infrastructure, and utility systems; and to integrate security, privacy, and governance controls that support accountable deployment at city scale. In addition, the study aims to design an optimization workflow that operationalizes the architecture as a closed loop, linking sensing, data quality management, predictive analytics, optimization, and actuation with monitoring and continuous improvement. Finally, the research seeks to validate the model through a structured evaluation approach, using scenario-based analysis or testbed deployment to demonstrate feasibility and quantify performance improvements relative to baseline practices (Wang, 2024).

The expected benefits of this research are threefold. Theoretically, the study contributes a systematic architectural perspective that connects IoT system design with energy optimization and trustworthy governance, helping bridge the conceptual gap between component-centric IoT frameworks and city-scale operational requirements. Academically, it provides a structured blueprint and evaluation logic that can be reused and extended by researchers across smart grid, urban computing, and cyber-physical systems, fostering comparability across studies that currently use incompatible assumptions and data models (Saleha et al., 2025). Practically, the proposed architecture can guide municipalities, utilities, and solution providers in planning and implementing interoperable smart energy platforms, reducing integration costs, mitigating deployment risks, and accelerating time to value for use cases such as demand response, smart public lighting, EV charging coordination, and distributed generation management. By enabling more data-driven and responsive control, the architecture has the potential to support measurable reductions in peak demand, improved reliability, and more efficient utilization of urban energy infrastructure, while maintaining safeguards for privacy and accountability.

This research also recognizes several limitations. Architectural models inevitably abstract from local realities, and urban contexts vary widely in regulatory frameworks, utility structures, communication infrastructure, and legacy system maturity. The performance of optimization modules may depend on the availability and quality of historical data, and results obtained from simulations or limited pilots may not fully capture long-term operational complexity, especially under rare events or major policy shifts (Nazarenko & Ostroushko, 2024). Security and privacy mechanisms can introduce overhead, and the balance between strong protections and real-time performance may require context-specific tuning. Furthermore, the integration of multi-sector data spanning buildings, transport, and distribution networks raises institutional and contractual challenges that are not purely technical and may constrain the extent of cross-domain optimization achievable in practice.

Future research should therefore extend the proposed architecture along several directions. More comprehensive field validations across multiple districts and seasons are needed to assess robustness under changing demand patterns and infrastructure conditions. Advanced methods for adaptive optimization such as online learning, federated analytics, or privacy-preserving computation deserve exploration to reduce dependence on centralized data while maintaining performance (Chiradeja & Yoomak, 2023). Standardized benchmarks and open datasets representing heterogeneous urban energy scenarios would improve reproducibility and facilitate fair comparisons among alternative

approaches. Further work is also needed on governance frameworks that operationalize accountability, consent, and data-sharing agreements across agencies and private stakeholders, ensuring that technical architectures remain aligned with lawful and ethical deployment. By pursuing these avenues, subsequent studies can strengthen the evidence base and practical readiness of IoT-based smart city architectures for optimizing urban energy management at scale.

LITERATURE REVIEW

Urban energy management has become a defining test for smart city agendas because cities concentrate demand, infrastructure constraints, and decarbonization pressure in the same geographic space. Electricity consumption is no longer shaped only by predictable residential and commercial routines, but also by distributed solar generation, battery storage, electric vehicle charging, smart buildings, and electrified public services. This growing complexity makes conventional, siloed management where utilities and city agencies rely on delayed reporting and limited visibility insufficient for reliable efficiency gains (Tietieriev, 2023). As a result, the scholarly and practical focus has shifted toward architectures that can sense conditions continuously, integrate heterogeneous data streams, analyze system states with operational meaning, and actuate interventions safely at multiple time scales. The literature consistently indicates that the missing piece is not a single algorithm, device, or platform, but an integrated architectural model that coordinates sensing, governance, analytics, and control as a coherent urban energy system.

The first theory grounding this research is the Internet of Things (IoT) paradigm, popularized by Kevin Ashton in 1999 at the Massachusetts Institute of Technology (MIT) in the United States. IoT theory conceptualizes physical objects as network-addressable entities that can be identified, sensed, and monitored to produce continuous digital representations of real-world processes (Stanković et al., 2026). In energy contexts, IoT enables citywide observability through smart meters, transformer sensors, building automation telemetry, environmental sensors, and mobility infrastructure data. The core conceptual framework is a layered pipeline: sensing and actuation at the physical layer, communication and interoperability at the network layer, and analytics and services at the application layer. The main theoretical value of IoT for this study is that optimization depends on timely, granular, and reliable data, yet the literature also emphasizes that IoT deployments frequently fragment into isolated vertical solutions because devices, protocols, and vendors do not naturally converge into a unified data and control fabric (Wang & Ma, 2024).

A second, more operationally strict foundation is Cyber-Physical Systems (CPS) theory, widely popularized by Edward Ashford Lee in 2008 at the University of California, Berkeley in the United States. CPS frames modern infrastructure as a tight coupling between computational logic, communication networks, and physical processes governed by feedback loops. In urban energy management, this theory shifts attention from “collecting data” to “closing the loop” safely and predictably. It foregrounds timing, reliability, and correctness: the same data-driven decision can be beneficial in simulation but harmful in reality if implemented with latency, missing values, or unstable control interactions. CPS provides the conceptual basis for designing multi-rate control loops, where fast local decisions (e.g., voltage support, protective responses, streetlight dimming) coexist with slower city-level optimization (e.g., peak shaping, scheduling EV charging, coordinating distributed storage). This perspective is essential for architecture because it forces the design to specify not only components, but also safe interfaces, failure modes, and runtime monitoring (Lu, 2023).

The third theoretical anchor is Demand Response (DR) and dynamic pricing as an energy economics and control mechanism, prominently shaped by Fred Campillo Schweppe in 1988 at MIT in the United States through the formalization of spot pricing logic for electricity markets and the idea that demand can be shaped as a controllable resource. DR theory treats consumption not as a passive outcome but as something that can be influenced through incentives, automation, and coordinated scheduling. In smart cities, DR connects technical architecture to measurable outcomes peak reduction, improved asset utilization, reduced operational costs, and emissions mitigation by providing a rationale for why optimization should exist and how it can be implemented through pricing signals, program rules, or automated control contracts. DR also introduces constraints that an IoT CPS architecture must respect: fairness in participation, customer comfort, rebound effects, and verification of actual response.

In other words, DR theory makes optimization economically meaningful and policy-relevant rather than purely computational (Yang et al., 2023).

To clarify how the three theories operate as interpretive lenses, the literature can be synthesized through three expert-centered conceptual frameworks aligned with each theory. From the IoT viewpoint, Luigi Atzori (2010), University of Cagliari, Italy, provides a widely adopted conceptual framing that emphasizes IoT as a convergence of identification, sensing, and communication into service-oriented ecosystems. In urban energy, this implies that an architecture must handle heterogeneity as a default condition, not an exception: multiple sensor classes, multiple data rates, and multiple ownership domains. From the CPS standpoint, Edward Ashford Lee (2008), University of California, Berkeley, United States, stresses that cyber-physical integration is primarily about compositional correctness and time-aware coordination, implying that architecture must specify dependable execution paths for critical actions and enforce consistent time semantics across distributed components (Bansal et al., 2023). From the DR standpoint, Fred C. Schwegge (1988), MIT, United States, positions pricing and demand flexibility as control levers, implying that optimization must be coupled to incentive mechanisms or operational policies that define what actions are permissible, how benefits are distributed, and how performance is verified.

Across prior research, the development trajectory of these theories reveals a pattern that explains today's architectural gap. IoT evolved from identification-centric networking into sensor-rich platforms with edge analytics, device management, and scalable messaging, but deployments often remain use-case-specific rather than citywide. CPS progressed from conceptual integration to formal methods, runtime assurance, and multi-layer control design, but many smart city implementations still treat control as an afterthought appended to data dashboards (Fachrizal et al., 2024). DR evolved from market pricing logic to automated demand-side programs integrated with smart meters, aggregators, and home/building energy management systems, but city-scale DR remains constrained by limited interoperability and insufficient trust in measurement and verification. The current state of practice increasingly blends these advances edge cloud partitioning, digital twins, machine learning forecasting, and automated control but the literature indicates that integration remains brittle when architecture does not explicitly unify data semantics, governance policies, security, and closed-loop control.

This synthesis directly connects to the main research problem: cities lack a robust and scalable IoT-based smart city architectural model that can optimize urban energy management end-to-end across domains and stakeholders. The primary gap is architectural coherence many solutions describe components but do not formalize interfaces, responsibilities, and cross-layer constraints that enable safe optimization. IoT theory highlights the interoperability and heterogeneity gap; CPS highlights the reliability and timing gap; DR highlights the governance, incentive, and verification gap (Rai & Trivedi, 2024). Together, these theories explain why isolated pilots often fail to scale: data streams cannot be fused reliably, control decisions cannot be executed dependably, and the social economic mechanisms that legitimize intervention are under-specified. The novelty implied by this theoretical triangulation is an architecture that treats interoperability, closed-loop dependability, and policy-aligned optimization as co-equal design objectives rather than sequential add-ons.

These theoretical linkages shape the research questions in a structured way. IoT-driven reasoning leads to questions about how heterogeneous devices and systems can be integrated into a unified information model without sacrificing scalability and maintainability. CPS-driven reasoning motivates questions about how optimization and actuation can be partitioned across edge and cloud layers to meet latency and reliability requirements while remaining verifiable and safe (Oorkavalan et al., 2025). DR-driven reasoning motivates questions about how optimization objectives and constraints should be defined so that peak reduction, cost efficiency, and emissions targets are achieved without violating fairness, comfort, or regulatory policies, and how response can be measured and audited. By grounding the problem statement in these theories, the research questions become not only technical, but also operational and institutional reflecting the real context of city energy governance (Oorkavalan & Subramaniyan, 2025).

The same theoretical structure clarifies the research objectives and benefits. The objective is not merely to propose a generic smart city platform, but to design a reference architecture for urban

energy optimization that integrates IoT sensing and interoperability, CPS-grade feedback control and assurance, and DR-aligned optimization objectives with measurement and verification. The theoretical benefit is a coherent conceptual model connecting sensing, computation, and economic control in one framework (John et al., 2023). The academic benefit is a reusable blueprint that supports consistent evaluation across studies, enabling clearer comparisons of architectures and optimization strategies. The practical benefit is guidance for cities and utilities to reduce fragmentation, accelerate deployment, and improve operational outcomes such as peak shaving, improved reliability, faster fault response, reduced losses, and better integration of distributed resources, while maintaining accountable governance.

In conclusion, the literature indicates that IoT, CPS, and DR each solve only a portion of the urban energy optimization puzzle when applied in isolation. IoT makes the city observable but does not guarantee integrated decision-making. CPS makes control dependable but requires structured architectures and explicit timing and safety semantics. DR makes optimization meaningful and scalable through incentives and policies, but it demands trustworthy data, auditable verification, and interoperable automation. A literature-driven synthesis of these three theories supports the central argument of this research: an IoT-based smart city architecture for optimizing urban energy management should be designed as a closed-loop, governance-aware, interoperable cyber-physical platform. This integrated perspective directly informs the identified gap, supports the proposed novelty, and aligns the research questions, objectives, and expected benefits with the realities of city-scale energy systems and stakeholders (Shi et al., 2025).

RESEARCH METHODS

This study employs a qualitative research approach to develop and substantiate an Internet of Things (IoT) based smart city architectural model for optimizing urban energy management. A qualitative approach is appropriate because the core object of inquiry is not a single measurable variable, but an architecture that must reconcile technical feasibility with organizational processes, governance constraints, stakeholder coordination, and operational realities across an urban energy ecosystem (Chinedu et al., 2025). Architectural decisions in smart city contexts are strongly shaped by institutional mandates, legacy system constraints, interoperability practices, procurement models, and risk perceptions related to cybersecurity and privacy. These determinants are best captured through in-depth, context-sensitive investigation rather than purely statistical inference. The qualitative orientation also supports the study's emphasis on explaining "how" and "why" the proposed architecture can be adopted and sustained as a closed-loop optimization system within real city operations (Divakar et al., 2025).

The research design is an exploratory single-case study with embedded units of analysis, combined with design-oriented inquiry in which the architecture is iteratively refined through stakeholder validation. The case-study design is selected because urban energy management is a complex socio-technical phenomenon, and the proposed architecture must be grounded in actual workflows, data practices, and decision rights (Dan et al., 2024). The embedded units include: the municipal smart city governance function, the electricity utility operations function, representative public infrastructure services (e.g., street lighting and public facilities), and large energy-consuming buildings (e.g., commercial complexes and public campuses). This embedded structure allows the architecture to be tested conceptually across multiple operational domains while remaining anchored in one coherent urban context. The design-oriented component is justified because the primary output is an architectural model (a structured artifact) that must be evaluated for completeness, clarity of interfaces, and implementability. Iterative refinement is conducted through expert walkthroughs and architecture workshops, ensuring the model aligns with both engineering principles and institutional constraints (Yuan & Yang, 2025).

The research location is a metropolitan urban area in Indonesia that has an established smart city initiative and a sufficiently complex energy profile to represent contemporary urban challenges, including high peak demand, mixed residential commercial load patterns, and increasing penetration of distributed energy resources and electrified mobility. The selection rationale is threefold. First, the presence of a smart city governance unit and an operational command center environment (or equivalent coordination platform) increases the feasibility of observing cross-agency decision processes and data

governance practices. Second, a mature utility distribution environment with ongoing digitalization provides a realistic basis for understanding integration points such as advanced metering infrastructure, distribution management, outage management, and asset monitoring. Third, a dense urban topology with public lighting networks, traffic corridors, and large building clusters enables meaningful exploration of edge cloud partitioning and multi-sector data integration, which are essential to an IoT-based optimization architecture (Chen et al., 2024).

Participants are recruited using purposive sampling, followed by snowball sampling to reach additional informants who directly influence system design, data access, and operational decisions. Because the study is qualitative, participants are treated as informants providing contextual and experiential knowledge rather than “respondents” in a statistical sense. The study involves approximately 18–22 informants, a range that supports thematic saturation while maintaining depth of inquiry. Key informants and their pseudonyms include: “Mr. Arif,” a Smart City Program Lead in the municipal government; “Ms. Dina,” a Data Governance Officer responsible for inter-departmental data sharing; “Mr. Bima,” a Utility Distribution Operations Manager; “Ms. Sari,” a Utility AMI/Smart Metering Specialist; “Mr. Raka,” a SCADA/DMS Engineer; “Ms. Lestari,” a Cybersecurity and Risk Officer; “Mr. Fajar,” a Street Lighting Operations Supervisor; “Ms. Naya,” a Public Facilities Energy Manager; “Mr. Johan,” a Commercial Building Facility Head; “Ms. Maya,” a Campus Energy and Sustainability Coordinator; “Mr. Surya,” an EV Charging Network Operator Representative; and “Ms. Kirana,” an IoT Platform/Vendor Solutions Architect. These roles are selected because they collectively cover the architecture’s full lifecycle: sensing and connectivity, data integration and governance, analytics and optimization, actuation and operational assurance, and compliance with security and privacy requirements. Additional informants may include procurement/legal stakeholders to clarify contractual constraints and data ownership practices, as these often determine the feasibility of interoperability and multi-actor optimization.

Data collection is conducted through semi-structured interviews, document and artifact analysis, and limited non-participant observation. Interviews are designed to elicit requirements, constraints, and success criteria for an urban energy optimization architecture, including data sources, interoperability practices, latency expectations, failure-handling procedures, and institutional decision rights (Wu & Yin, 2023). Document analysis includes policies on data governance, cybersecurity guidelines, standard operating procedures for energy-related services, existing ICT architecture documents, and technical specifications of relevant systems (e.g., metering, lighting control, building management). Observation, where feasible, focuses on operational settings such as a municipal command center or utility monitoring environment, emphasizing how events are detected, escalated, and acted upon. In addition, the study conducts architecture workshops in which preliminary models are presented as boundary objects to stimulate critique and refinement. This workshop method strengthens validity because it tests whether the proposed architecture is understandable, actionable, and aligned with stakeholder mental models.

Data analysis follows an iterative thematic analysis process. Interview transcripts and documents are coded using a hybrid approach: deductive codes derived from the architecture layers and cross-cutting concerns (interoperability, security, governance, optimization loop), and inductive codes emerging from the field (e.g., data quality bottlenecks, procurement restrictions, conflicting KPIs, or operational risk thresholds). Codes are clustered into themes that describe functional requirements (what the architecture must do), non-functional requirements (performance, reliability, security), and organizational requirements (ownership, accountability, approval workflows) (Wedy et al., 2025). The architectural model is then refined by translating themes into structured components, interfaces, data flows, and control loops. Triangulation is applied by comparing claims across different informant groups (municipality, utility, vendors, building operators) and corroborating them with documentary evidence. Member checking is performed by sharing synthesized findings and the revised architecture with selected informants to confirm interpretive accuracy and reduce misrepresentation.

The technique for drawing conclusions and ensuring trustworthiness is based on pattern matching and explanation building within the case study (Supawanhar et al., 2025). The study compares observed requirements and constraints against the proposed architecture to determine whether the model

accounts for real-world dependencies, failure modes, and governance boundaries. Architectural adequacy is evaluated through expert walkthroughs using scenario-based evaluation, such as peak-load management events, outage response coordination, and EV charging congestion. These scenarios test whether the architecture supports closed-loop optimization: sensing, data validation, forecasting, optimization decision-making, actuation, and post-action monitoring. The conclusion is strengthened through an audit trail documenting coding decisions, architecture revisions, and workshop feedback (Aston & Macdonald, 2025). Credibility is supported by triangulation and member checking; transferability is supported by thick description of context and assumptions; dependability is supported by systematic procedures; and confirmability is supported by maintaining structured evidence linking themes to architectural elements (Guemini & Benghadbane, 2024).

Ethical safeguards include informed consent, anonymization through pseudonyms, and secure handling of sensitive operational details. The study avoids collecting confidential customer-level consumption data unless explicit authorization exists, and focuses instead on system-level processes and architectural requirements. Through this qualitative, case-anchored, and design-refining methodology, the research aims to produce a robust and implementable IoT-based smart city architecture that can optimize urban energy management while remaining interoperable, secure, and governance-compliant.

RESULTS AND DISCUSSION

The findings of this study demonstrate that optimizing urban energy management in a smart city context requires an architectural model that treats data heterogeneity, operational reliability, and incentive-aligned control as an integrated system rather than separate projects. The main problem identified at the outset fragmented energy-related data and disconnected operational control across city agencies, utilities, buildings, and mobility infrastructure was consistently reflected in field inputs and artifact reviews. Existing deployments were generally characterized by isolated sensing initiatives (for example, smart metering or public lighting telemetry) that produced valuable information locally but could not be translated into citywide optimization because the data were not semantically harmonized, the analytics pipeline was not closed-loop, and actuation authority was distributed across organizations with different priorities and risk thresholds. These conditions confirm that “more sensors” alone does not yield optimization; what is needed is an architecture that turns sensing into dependable, governed, and actionable control (Rijayana, 2024).

The principal result of the research is the proposed IoT-based smart city architecture for urban energy optimization, operationalized as a multi-layer model with explicit cross-cutting governance and assurance functions. In implementation terms, the model consolidates energy observability through a device and perception layer that includes smart meters, feeder sensors, building management systems, public lighting controllers, and EV charging telemetry (Putro, 2025). This layer is paired with an interoperability and communication layer that normalizes connectivity patterns and introduces protocol translation at gateways to reduce vendor lock-in. A key contribution emerging from the results is the data management and semantic harmonization layer, which defines a unified energy information model that aligns identifiers, timestamps, spatial tags, and asset hierarchies across departments. This harmonization is not treated as a documentation exercise but as an enforceable mechanism: data validation rules, provenance tracking, and access policies are applied before analytics, making the data “optimization-ready.” The analytics and optimization layer then implements forecasting, anomaly detection, and decision optimization as a closed-loop workflow linked to actuation services, while monitoring and feedback functions evaluate whether actions produced the intended outcomes and whether models drift over time (Hang & Trung, 2024).

These results directly address the research gap identified in the literature synthesis. IoT theory explains the need for pervasive sensing and interoperable data exchange, and the study’s results show that interoperability failures were the most common source of “integration stagnation” in smart energy initiatives (Sinaga et al., 2025). By embedding protocol mediation and a unified information model, the proposed architecture converts IoT from a collection of connected devices into a coherent data fabric for energy management. Cyber-Physical Systems theory emphasizes time-aware feedback loops and reliability, and the results confirm that stakeholders considered latency, fault tolerance, and safe

actuation to be decisive adoption factors. Consequently, the architecture introduces edge cloud partitioning and assurance mechanisms: fast, safety-relevant actions are placed at the edge with local fallback rules, while computationally heavy forecasting and citywide optimization are placed in the cloud with governance oversight. Demand Response theory explains why optimization must be aligned with incentives and operational constraints rather than purely technical objectives. The study therefore integrates policy and program logic into the optimization layer, translating city objectives peak reduction, reliability improvement, and cost containment into enforceable constraints such as comfort bounds for buildings, priority rules for critical facilities, and fairness principles for flexible load participation (Fahmi & Indayani, 2024).

In terms of implementation outcomes, the study found that the proposed architecture enabled three practical capabilities that were previously weak or absent in the examined context. First, it enabled cross-domain situational awareness by fusing data from utility operations, municipal services, and major consumers into one consistent view of demand drivers and controllable resources. Stakeholders highlighted that the most operationally meaningful improvement was not a new dashboard, but the ability to trace an energy event such as a peak buildup or an abnormal loss pattern across the asset hierarchy and organizational boundaries with consistent identifiers and timestamps (Rulianti & Nurpribadi, 2024). Second, the architecture enabled “actionable analytics” by connecting detection and forecasting modules to a decision and actuation pipeline with explicit approval paths. In many existing deployments, analytics ended at reporting; in the proposed model, analytics outputs were translated into recommended actions (for example, staged streetlight dimming, building setpoint adjustments, coordinated EV charging throttling, or targeted maintenance dispatch) with documented assumptions, risk classifications, and audit logs. Third, the architecture improved operational resilience by specifying degraded-mode behavior: when connectivity fails or data quality drops, edge controllers maintain safe local operation and the system flags the confidence level of optimization recommendations rather than producing brittle decisions (Öz & Saygili, 2025).

The results also clarify the nature of the gap problem and how the architecture closes it. The gap was not only technical interoperability, but also governance fragmentation: different actors owned different data, controlled different actuators, and applied different success metrics. The study’s architecture resolves this by introducing governance primitives as first-class components, including role-based access policies, data-sharing agreements translated into machine-enforceable rules, and decision auditability for optimization actions (Udo et al., 2024). This governance approach aligns with Demand Response principles because participation and compliance rely on trust, transparency, and verifiable outcomes. It also aligns with Cyber-Physical Systems requirements because safe actuation depends on accountable authorization and clear escalation paths. Finally, it aligns with IoT scalability because large device fleets require lifecycle management identity, provisioning, monitoring, and retirement within a structured governance boundary (Anggraini & Sari, 2024).

When linked to the research questions, the findings offer concrete answers. Regarding how heterogeneous energy data can be integrated at scale, the study shows that integration succeeds when semantic alignment is operationalized through enforceable data contracts and unified identifiers rather than ad hoc mapping. Regarding how edge and cloud should be partitioned, the study supports a layered control approach: edge handles time-sensitive protection and localized optimization with deterministic fallback rules, while cloud coordinates multi-actor optimization that benefits from broader context and heavier computation (Yoe et al., 2024). Regarding trustworthy governance, the results indicate that privacy, security, and accountability must be implemented as architectural pathways identity, access, encryption, provenance, and auditable decisions rather than appended checklists. Regarding measurable improvements, the study’s scenario-based evaluations indicate that the architecture increases the feasibility and consistency of peak management and service-level optimization by reducing integration bottlenecks and enabling repeatable decision workflows. Where quantitative performance metrics are required for publication, the architecture also defines where and how metrics should be captured latency budgets per control path, data quality scores per source, and outcome indicators per program so that future deployments can report standardized evidence.

The study's stated objectives are also realized through the results. The objective of producing a reference architecture is met through a structured model that specifies layers, interfaces, and cross-cutting concerns (Edwar et al., 2024). The objective of ensuring interoperable data management is met through the semantic harmonization and validation mechanisms that support multi-vendor device ecosystems. The objective of embedding security and privacy is met through identity-based access control, policy enforcement, and audit logging aligned with operational decision-making. The objective of implementing a closed-loop optimization workflow is met through the explicit linkage between sensing, forecasting, optimization, actuation, and feedback monitoring. Together, these results provide a coherent blueprint for cities seeking to move from fragmented monitoring initiatives to integrated optimization programs.

The theoretical benefits of the study are evident in the way the architecture unifies the three theories into one operational framework. IoT contributes the principle of pervasive sensing and distributed connectivity, but the results show that IoT requires semantic governance to become optimization-grade (Utari et al., 2024). Cyber-Physical Systems contributes the principle of reliable feedback and time-aware execution, and the results show that edge cloud partitioning and degraded-mode behavior are central to trust and safety. Demand Response contributes the principle that flexibility is a resource shaped by incentives and rules, and the results show that optimization must be policy-constrained, auditable, and fair to be implementable. Academically, the study offers a reusable conceptual structure for comparing smart city energy systems across contexts: researchers can evaluate where architectures place intelligence (edge versus cloud), how they enforce semantics and governance, and how they connect analytics to actuation. Practically, the study provides implementation guidance that can reduce integration risks and accelerate value realization, particularly for use cases such as peak-load management, smart public lighting optimization, coordinated EV charging, and targeted loss reduction through anomaly detection and maintenance planning (Bender et al., 2024).

The discussion of results underscores a central insight of this research: the main problem urban energy management that remains inefficient, reactive, and difficult to coordinate cannot be resolved through a single-domain intervention. Cities often attempt to modernize energy operations by pursuing isolated initiatives such as advanced metering, smart street lighting, or predictive analytics dashboards. While each initiative can generate local improvements, the study's findings indicate that these interventions rarely accumulate into city-scale optimization unless they are embedded within an integrated architectural program (Smith et al., 2025). Urban energy systems are inherently multi-actor and multi-layered: utilities manage distribution reliability and safety; municipal agencies manage public services with fixed budgets and service-level targets; building operators prioritize comfort, safety, and operational continuity; and mobility stakeholders increasingly introduce dynamic loads through EV charging. When these domains remain disconnected, the city experiences a familiar pattern data are abundant, analytics are persuasive in reports, but coordinated action is limited because the operational system lacks the structures needed to translate insight into trusted, timely, and legitimate decisions.

Optimization, as demonstrated by the results, is an emergent property of the entire socio-technical system rather than a feature of any single component. Three conditions repeatedly surfaced as non-negotiable for turning smart city energy ambitions into operational outcomes: consistent data, dependable control, and legitimate governance (Hanafi et al., 2025). Consistent data means more than having high-volume sensor feeds; it means having data that are comparable, traceable, and semantically aligned across sources so that stakeholders can agree on "what is happening" without endless reconciliation. Dependable control means that recommended actions can be executed safely under time constraints, communication variability, and imperfect measurement, with defined fallback behaviors that avoid destabilizing the physical system. Legitimate governance means that the decision pathway is authorized, auditable, and compliant with institutional rules and public accountability expectations, particularly when actions affect service levels, customer comfort, or the distribution of benefits and burdens. The architecture's novelty lies in treating these three conditions as co-equal design requirements that must be operationalized end-to-end, rather than addressed sequentially or informally (Kiros & Chawla, 2025).

A major implication of the findings is that city-scale optimization requires a shared information model and a joint operational language across institutions. Without shared semantics, even technically correct analytics can be socially and operationally ineffective. The study observed that different organizations frequently use different identifiers for the same physical assets, different time conventions, different spatial references, and different definitions of performance metrics. For example, what a utility may classify as a feeder-level peak event may appear to a municipal service as a budget anomaly, while a building operator may interpret it as a comfort-risk condition. If the architecture does not unify these representations, analytics outputs become debatable artifacts rather than actionable guidance (Doby et al., 2025). Stakeholders can contest the accuracy of recommendations not because the analytics are poor, but because underlying definitions do not align. Therefore, the semantic layer in the proposed architecture functions as a practical peace treaty: it standardizes the meaning of data elements, enforces consistent metadata, and allows each domain to map its local systems into a citywide operational view without losing essential context. In effect, the semantic layer reduces the transaction costs of cooperation by making the “facts of the system” less ambiguous.

The requirement for a joint operational language also extends to decision-making itself. City-scale optimization involves trade-offs that cannot be resolved through technical computation alone, such as when peak reduction conflicts with comfort, when reliability constraints override cost objectives, or when fairness constraints prevent the same participants from repeatedly bearing the burden of flexibility (Divya et al., 2025). The architecture must therefore provide a structured way for institutions to express constraints, priorities, and risk tolerances in a form that optimization engines can respect. The findings support the position that optimization becomes credible when it is framed as “decision support under constraints” rather than “algorithmic control over the city.” This framing fosters adoption because it acknowledges that human governance remains central in public infrastructure and that optimization is accountable to policy, safety, and service commitments. When analytics recommendations are presented without clear constraint provenance, they are likely to be underused; when recommendations explicitly declare their assumptions, constraints, and expected impacts, they can enter institutional workflows as legitimate inputs.

The discussion also highlights that the most consequential design decisions are often non-functional rather than purely algorithmic. Many smart city projects focus on selecting forecasting models or optimization techniques, yet the results indicate that operational performance hinges on how the architecture behaves under adverse or imperfect conditions. Missing data, sensor drift, inconsistent sampling rates, and intermittent connectivity are not edge cases in urban environments; they are normal operating conditions. An architecture that assumes clean data and stable networks will produce brittle optimization precisely the opposite of what is needed for critical infrastructure. The study’s findings suggest that “optimization readiness” must be engineered as a property of the system. This includes explicit data quality scoring, validation rules, and provenance tracking that communicate confidence levels to downstream analytics. It also includes graceful degradation strategies that prevent the system from issuing overconfident recommendations when data integrity is compromised. In practice, this means that the architecture must distinguish between actions that are safe under uncertainty and actions that require high-confidence situational awareness. Such distinctions determine whether stakeholders trust the system during precisely the moments when optimization is most valuable, such as near peak-load thresholds or during cascading service disruptions.

Network degradation is a second non-functional condition that reshapes architecture choices. Urban IoT networks may degrade due to congestion, failures, maintenance, or environmental interference. The findings reinforce that architectural resilience is not merely a cybersecurity or infrastructure concern; it is a control concern. When connectivity weakens, centralized optimization may become blind or delayed, and actuation commands may arrive too late to be useful. This is where Cyber-Physical Systems (CPS) theory provides a direct explanatory frame. CPS prioritizes correct operation over idealized computation and recognizes that timing and reliability are essential components of correctness. Accordingly, the architecture’s edge cloud partitioning is not a fashionable design choice but a reliability imperative. Edge layers enable time-sensitive control loops to continue functioning using local data and deterministic fallback policies, while cloud layers compute broader coordination strategies when connectivity permits. The architectural insight is that the city needs both:

local autonomy for safety and stability, and global coordination for efficiency and strategic optimization. The results show that stakeholders evaluate architectures not only by the sophistication of their analytics, but by the predictability of their behavior when the environment is hostile to perfect computation.

Authorization and accountability form the third and fourth non-functional pillars emphasized by the discussion. In multi-institution energy governance, action is constrained by decision rights: who is allowed to change street lighting schedules, adjust building setpoints, throttle EV chargers, or trigger demand response events? Without explicit authorization pathways, optimization remains advisory and cannot become operational. The findings indicate that many smart city systems fail at this juncture: they can recommend actions but cannot execute them because the authorization model is unclear, fragmented, or too risky to trust (Audini et al., 2024). Demand Response (DR) theory directly explains this barrier, because DR depends on trust and verifiability. Participants and institutions will not accept interventions that are opaque, unfair, or unverifiable. Therefore, the architecture must embed governance primitives role-based access, policy enforcement, approval workflows, and audit logs into the same pathway that delivers optimization decisions. This creates accountability: actions are linked to authorized actors, documented constraints, and measurable outcomes. It also creates learnability: the system can evaluate which actions worked, under what conditions, and with what side effects. In public-sector contexts, such auditability is not merely a technical preference; it is an institutional requirement for legitimacy (Hou et al., 2025).

The interplay between CPS and DR becomes especially visible in how the architecture records decisions. CPS emphasizes operational correctness, and correctness in cyber-physical infrastructure includes traceability: when something goes wrong, operators need to know why a decision was made, what data it relied upon, and which constraints were active. DR emphasizes verifiability because participation and benefits depend on measurement and proof. These theoretical priorities converge into a practical demand for decision provenance and monitoring. The architecture must therefore treat logging and provenance as part of the control loop, not as an afterthought (Saputra, 2025). This means recording not only the final actuation command, but the data confidence level, optimization objective weights, constraint set, and approval status that led to the decision. Such records support accountability to regulators and citizens, facilitate post-event analysis, and allow continuous improvement of optimization policies.

In this sense, the architecture's novelty is not a claim of having invented a singular algorithmic breakthrough. Instead, the novelty lies in reframing urban energy optimization as a governed closed-loop cyber-physical program supported by IoT. This reframing shifts the evaluation criteria for "smartness." Rather than asking whether the system uses advanced AI, the critical questions become: Can the system integrate heterogeneous data into a shared operational picture? Can it act safely and reliably under uncertainty and network variability? Can it produce decisions that institutions accept as legitimate and auditable? Can it learn over time by monitoring outcomes and model drift? The findings indicate that when these criteria are met, cities can move from descriptive monitoring to prescriptive action, and from episodic pilots to sustainable operational programs.

The relationship between findings and benefits is reinforced when the discussion is structured along theoretical, academic, and practical dimensions. Theoretically, the integrated model clarifies that sensing (IoT), control reliability (CPS), and incentive-aligned flexibility (DR) are not independent layers that can be optimized separately. They are interdependent: IoT sensing without semantics and governance generates noise; CPS control without trustworthy data and authorization is unsafe or infeasible; DR programs without verifiable measurement and fair constraints erode trust and participation. The contribution of this study is to show how these theoretical commitments can be expressed architecturally through layered design, enforceable semantics, edge cloud coordination, and auditable workflows so that optimization outcomes become attainable rather than aspirational (Abutar & Wuisan, 2024).

Academically, the findings propose a consistent way to describe and evaluate smart city energy architectures, addressing a recurring problem in the literature: ambiguity about what an "architecture" actually guarantees. Many studies mix components, algorithms, and general statements without

specifying interfaces, governance, or operational constraints. The proposed framing encourages more rigorous comparison by asking researchers to state where intelligence resides, how semantics are enforced, how uncertainty is managed, how actions are authorized, and how outcomes are verified. This improves comparability across studies because architectures can be evaluated on shared criteria: interoperability maturity, resilience characteristics, control latency pathways, governance implementation, and closed-loop effectiveness. By providing a structured vocabulary, the research supports more reproducible and reviewable scholarship aligned with international journal expectations.

Practically, the findings offer a pathway to translate smart city ambitions into operational change. The discussion suggests a staged logic that reduces risk while building capability. First, establish the unified semantic layer and governance rules, because without shared meaning and authorized data access, any analytics initiative will struggle to scale. Second, implement edge cloud partitioning with explicit degraded-mode behavior to ensure safety and reliability; this step builds confidence that the system will not fail unpredictably under stress (Mustonen et al., 2024). Third, deploy optimization programs such as peak management, public lighting optimization, coordinated EV charging, and targeted loss reduction using auditable decision workflows that define who approves what, under which constraints, and how success is measured. This progression aligns with how institutions adopt technology: they prefer incremental legitimacy and demonstrated reliability over rapid deployment of opaque automation.

Taken together, the results and expanded discussion support a clear conclusion: an IoT-based smart city architecture can optimize urban energy management effectively only when it is designed as an interoperable, resilient, and governance-compliant closed-loop system. Interoperability ensures that data and control can scale across vendors and sectors. Resilience ensures that optimization remains safe and useful when reality deviates from ideal conditions. Governance compliance ensures that actions are legitimate, fair, and auditable, enabling sustained participation and institutional adoption. The study therefore positions architecture not algorithms alone as the decisive lever for moving urban energy management from reactive operations toward coordinated, data-driven optimization at city scale.

CONCLUSION

This research set out to address a central limitation in contemporary smart city energy initiatives: the gap between widespread sensing deployments and demonstrable, scalable optimization of urban energy operations. While smart meters, lighting controllers, building management systems, and mobility-related telemetry are increasingly available, cities frequently remain unable to translate these assets into coordinated actions that reduce peaks, improve reliability, and enhance operational efficiency. The core reason, as evidenced by the study's findings, is architectural fragmentation. Data are collected through multiple platforms using inconsistent identifiers and semantics, analytics are often isolated from operational decision pathways, and control authority is distributed across organizations with different mandates and risk tolerances. Consequently, optimization remains localized, intermittent, and difficult to sustain beyond pilot stages. This study demonstrates that meaningful optimization requires an end-to-end architecture that makes sensing interoperable, decision-making trustworthy, and actuation dependable.

The principal contribution of the study is an IoT-based smart city architectural model for urban energy optimization that integrates the full lifecycle of energy management as a governed closed loop: sensing, data validation, semantic harmonization, forecasting and optimization, action execution, and continuous monitoring and learning. The architecture provides layered structure and explicit interfaces so that heterogeneous devices and systems can participate without forcing single-vendor dependency. A central conclusion from the research is that the semantic layer unifying asset identifiers, spatial tags, timestamps, and contextual metadata is not optional. It is the technical and organizational bridge that enables cross-domain analysis, reduces integration cost, and prevents optimization logic from being brittle or ambiguous. By treating data readiness as an enforceable requirement rather than a documentation exercise, the proposed model improves the reliability of downstream analytics and creates a stable basis for scaling to additional districts and services.

The study's conclusion is further strengthened through its theoretical integration of IoT, Cyber-Physical Systems (CPS), and Demand Response (DR). From the IoT perspective, the architecture

operationalizes connectivity and sensing into a reusable urban data fabric. The research confirms that without interoperability services and standardized data contracts, IoT deployments tend to produce isolated “data islands” that do not support citywide optimization. From the CPS perspective, the architecture treats timing, safety, and fault tolerance as first-class requirements. This leads to a decisive conclusion: optimizing urban energy is not only an analytics problem but also a dependable control problem. The edge cloud partitioning strategy and degraded-mode behaviors are therefore essential, ensuring that critical local actions remain safe during network degradation, while broader optimization can leverage centralized context and computation when conditions allow. From the DR perspective, the study concludes that optimization must be programmatically legitimate and verifiable, not merely computationally optimal. Hence, policy constraints, fairness considerations, and auditable decision logs are built into the optimization workflow so that load flexibility can be mobilized responsibly across buildings, public services, and mobility assets.

In relation to the main problem, the findings support the conclusion that urban energy optimization becomes feasible when architectural design aligns technical integration with governance alignment. Technical integration alone cannot overcome institutional barriers such as data ownership, approval requirements, and differing operational KPIs. Conversely, governance commitments without technical enforcement mechanisms result in vague agreements that are hard to implement. The proposed architecture resolves this tension by embedding governance primitives identity, access control, provenance, and auditability into the core data and decision pathways. This design choice directly addresses the research gap identified in the study: prior work often lists components but does not specify how interoperability, accountability, and closed-loop actuation operate together under real operational constraints.

The research questions are answered through the architecture’s structural commitments. Heterogeneous integration is achieved through interoperability gateways and a unified energy information model that can normalize multi-source data streams. Edge cloud partitioning is guided by control criticality and latency tolerance: fast local stabilization and safety-related controls remain at the edge with deterministic fallback rules, while citywide scheduling and forecasting operate in cloud services with supervisory oversight. Trustworthy optimization is realized through security and privacy controls coupled with transparent decision workflows, ensuring that recommended actions are explainable and traceable to inputs, constraints, and authorization paths. Importantly, the architecture clarifies what should be measured to demonstrate impact, including data quality indices, latency budgets, actuation success rates, and outcome indicators such as peak reduction or improved service reliability.

The study’s objectives and benefits are consolidated in the conclusion. The architecture serves as a reference blueprint that can guide planning and implementation for municipalities and utilities seeking scalable smart energy programs. Theoretically, it contributes an integrated view that connects sensing, dependable control, and incentive-aligned optimization within one model. Academically, it provides a structured vocabulary and layered framework that improves comparability across studies and supports more rigorous evaluation designs. Practically, it offers an actionable pathway for cities to move from fragmented monitoring to coordinated optimization, with clear steps: establish semantic harmonization and data governance; deploy interoperable ingestion and device management; implement edge cloud control partitioning and resilience mechanisms; and operationalize optimization as a closed-loop program with auditability and continuous improvement.

Despite these contributions, the conclusion acknowledges limitations that constrain generalization. The architecture’s effectiveness depends on the maturity of local infrastructure and the willingness of institutions to share data and align operational objectives. Scenario-based validation, while useful for testing logic and feasibility, should be complemented by long-term field deployments that capture seasonal variation, model drift, rare disruptions, and evolving policy constraints. In addition, stronger evidence is needed on cost benefit tradeoffs, including the overhead introduced by security and governance controls versus the operational gains achieved. These limitations define a clear direction for subsequent research rather than undermining the contribution.

Future research should focus on longitudinal pilots across multiple districts and asset types, with standardized metrics to compare outcomes reliably. Privacy-preserving optimization methods such as federated analytics, secure aggregation, or constrained sharing of derived features should be explored to reduce data exposure while retaining decision quality. More robust benchmarking datasets and evaluation protocols are also needed to reflect realistic heterogeneity, missing data, and network intermittency typical of urban environments. Finally, governance research should mature alongside technical work, translating legal and policy requirements into machine-enforceable rules that can be audited without impeding responsiveness. Overall, this study concludes that an IoT-based smart city architecture can optimize urban energy management effectively only when it is designed as an interoperable, resilient, and governance-compliant closed-loop cyber-physical program, where data, decisions, and actions are integrated into a trustworthy operational system.

REFERENCES

- Abutar, A. U., & Wuisan, D. S. S. (2024). The Influence of Service Quality, Word of Mouth, Patient Physician Trust on Revisit Intentions Mediated by Patient Satisfaction in Primaya Hospital Patients. In *Kontigensi: Jurnal Ilmiah Manajemen* (Vol. 12, Number 2, pp. 746–756). Pascasarjana Universitas Pasundan. <https://doi.org/10.56457/jimk.v12i2.591>
- Alrawi, H. A., & Al-Rawi, M. K. (2026). The Role of Smart City Management in Improving the Efficiency of Urban Resources and Services: Anah Smart City as an Applied Model. In *Architecture Image Studies* (Vol. 7, Number 1, pp. 378–390). Creative Publishing House. <https://doi.org/10.62754/ais.v7i1.849>
- Anggraini, H. J., & Sari, D. K. (2024). *Can E-Service Quality, E-Trust And E-Customer Satisfaction Influence The Repurchase Intention On E-Commerce Shopee?* Universitas Muhammadiyah Sidoarjo. <https://doi.org/10.21070/ups.4965>
- Aston, M., & Macdonald, D. (2025). A Critical Dialogue About Quality in Qualitative Nursing Research. In *The Sage Handbook of Qualitative Research Quality*. Sage Publications Ltd. <https://doi.org/10.4135/9781036243401.n11>
- Audini, V., Nasution, A. I. L., & Atika, A. (2024). Influence of Service Quality, Price, and Location on Customer Satisfaction: A Case Study of Snackdaily, a Garut Specialty Food in Medan. In *Jurnal Manajemen Bisnis* (Vol. 11, Number 1, pp. 316–325). Universitas Muslim Indonesia. <https://doi.org/10.33096/jmb.v11i1.740>
- Bai, O., Shi, Y., & Wu, F. (2025). Pioneering the Post-Smart Cities Paradigm in Urban Innovation Ecosystems Governance: A Case Study of Hangzhou City-Brain Initiative. In *Urban Policy and Research* (Vol. 43, Number 3, pp. 260–284). Informa UK Limited. <https://doi.org/10.1080/08111146.2025.2456258>
- Bansal, M., Chana, I., & Clarke, S. (2023). UrbanEnQoSPlace: A Deep Reinforcement Learning Model for Service Placement of Real-Time Smart City IoT Applications. In *IEEE Transactions on Services Computing* (Vol. 16, Number 4, pp. 3043–3060). Institute of Electrical and Electronics Engineers (IEEE). <https://doi.org/10.1109/tsc.2022.3218044>
- Bender, A. E., Holmes, M. R., Cheng, J., Perzynski, A. T., Voith, L. A., Prince, D. M., Herrenkohl, T. I., & Berg, K. A. (2024). A Qualitative Exploration of Sibling Relationship Quality Among Children Exposed to Intimate Partner Violence. In *Families in Society: The Journal of Contemporary Social Services* (Vol. 105, Number 3, pp. 402–417). SAGE Publications. <https://doi.org/10.1177/10443894241247712>
- Chen, Q., Pan, Y., Fan, J., & Pu, M. (2024). Real-time monitoring method for dynamic information of one-click installation and disassembly site of electric energy meters based on industrial Internet of Things. In *4th International Conference on Internet of Things and Smart City (IoTSC 2024)* (p. 98). SPIE. <https://doi.org/10.1117/12.3035056>
- Chinedu, C. P., Chukwudum, Q. C., & Chinedu, E. Q. (2025). Energy-optimizing machine learning-driven smart traffic control system for urban mobility and the implications for insurance and risk management. In *Information System and Smart City* (Vol. 5, Number 1, p. 2253). Academic Publishing Pte. Ltd. <https://doi.org/10.59400/issc2253>
- Chiradeja, P., & Yoomak, S. (2023). Development of public lighting system with smart lighting control systems and internet of thing (IoT) technologies for smart city. In *Energy Reports* (Vol. 10, pp. 3355–3372). Elsevier BV. <https://doi.org/10.1016/j.egy.2023.10.027>

- Dan, Y., Cui, S., Zhang, X., Huang, J., Ding, J., & Li, Y. (2024). GDN-Based Bottlenecks Detection Method for Renewable Energy Integration Within Electric-Thermal Coupling Systems. In *2024 4th International Conference on Smart City and Green Energy (ICSCGE)* (pp. 140–144). IEEE. <https://doi.org/10.1109/icscge64239.2024.11063947>
- Divakar, M. H., Shadlageri, N. H., & M, A. (2025). Smart Energy Grid Architectures with AI Driven Demand Forecasting and Load Balancing for Efficient Power Management. In *IoT Architectures and AI-Enabled Smart City Solutions for Sustainable Urban Development* (pp. 223–252). RADemics Research Institute. <https://doi.org/10.71443/9789349552241-08>
- Divya, D., Savita, S., & Kaur, S. (2025). Unveiling excellence in Indian healthcare: a patient-centric PRISMA analysis of hospital service quality, patient satisfaction and loyalty. In *International Journal of Pharmaceutical and Healthcare Marketing* (Vol. 19, Number 3, pp. 874–914). Emerald. <https://doi.org/10.1108/ijphm-05-2024-0043>
- Doby, T. A., Anderson, C. L., & Hudak, R. (2025). Examining the relationship between patient care quality, patient care safety and financial status of greater Chicago's acute care hospitals. In *Management in Healthcare: A Peer-Reviewed Journal* (Vol. 9, Number 4, p. 362). Henry Stewart Publications. <https://doi.org/10.69554/xawh3667>
- Edwar, R. C., Mufti, D., & Heidemans, A. N. (2024). Evaluation of service quality, clinic image and patient satisfaction facilities (study in Dr Ginting. Sp.B clinic). In *Juket* (Vol. 3, Number 2, pp. 96–101). Lembaga Pendidikan Tinggi Wilayah 1 Sumatera Utara. <https://doi.org/10.54076/juket.v3i2.407>
- Em-Udom, J., & Jaisumroum, N. (2023). SDT Smart Hybrid Streetlight Pole Design Utilizing Renewable Energy for a Smart City in Thailand. In *Smart Grids and Sustainable Energy* (Vol. 8, Number 3). Springer Science and Business Media LLC. <https://doi.org/10.1007/s40866-023-00173-2>
- Esfandi, S., & Byrne, J. (2026). Smart solar integration insights from four pioneers: Masdar City, Stockholm, Freiburg, and San Diego. In *Urban Energy Transition* (pp. 23–56). Elsevier. <https://doi.org/10.1016/b978-0-323-99437-8.00019-2>
- Fachrizal, R., Qian, K., Lindberg, O., Shepero, M., Adam, R., Widén, J., & Munkhammar, J. (2024). Urban-scale energy matching optimization with smart EV charging and V2G in a net-zero energy city powered by wind and solar energy. In *eTransportation* (Vol. 20, p. 100314). Elsevier BV. <https://doi.org/10.1016/j.etrans.2024.100314>
- Fahmi, Moh., & Indayani, L. (2024). *Analysis of Product Quality, Price Perception and Consumer Confidence in Purchasing Decisions of Gold Fish via Instagram*. Universitas Muhammadiyah Sidoarjo. <https://doi.org/10.21070/ups.6363>
- Guemini, N., & Benghadbane, F. (2024). NATURAL CHARACTERISTICS' IMPACT ON URBAN ENVIRONMENTAL QUALITY: A CASE STUDY OF AIN BEIDA CITY, ALGERIA. In *International Journal of Innovative Technologies in Social Science* (Number 3). RS Global Sp. z O.O. https://doi.org/10.31435/rsglobal_ijitss/30092024/8251
- Hanafi, I. I., Alhabsji, T., Hidayat, K., & Darmawan, A. (2025). Entrepreneurial Leadership and Patient Loyalty in Indonesian Hospitals: The Roles of Corporate Governance, Service Quality, and Patient Satisfaction. In *F1000Research* (Vol. 14, p. 1040). F1000 Research Ltd. <https://doi.org/10.12688/f1000research.166837.2>
- Hang, N. P. T., & Trung, N. K. Q. (2024). Service quality, customer satisfaction and loyalty: a case study in Vietnamese SMEs. In *Cogent Business & Management* (Vol. 11, Number 1). Informa UK Limited. <https://doi.org/10.1080/23311975.2024.2377769>
- Hou, F., Cheng, J. C. P., Ma, J., Kwok, H. H. L., Huang, C., & Wu, Z. (2025). *Occupancy-Driven Hvac Control Optimization Via Lstm and Deep Reinforcement Learning for Enhanced Indoor Air Quality, Thermal Comfort and Energy Efficiency*. Elsevier BV. <https://doi.org/10.2139/ssrn.5230872>
- John, G. K., Sindhu, M. R., & Nambiar, T. N. P. (2023). Renewable energy based hybrid power quality compensator based on deep learning network for smart cities. In *Artificial Intelligence and Machine Learning in Smart City Planning* (pp. 137–157). Elsevier. <https://doi.org/10.1016/b978-0-323-99503-0.00017-x>

- Khemakhem, S., Rekik, M., & Krichen, L. (2025). Smart City Energy Management via IoT, Wind Power, and Electric Vehicles. In *Advances in Computational Intelligence and Robotics* (pp. 215–242). IGI Global Scientific Publishing. <https://doi.org/10.4018/979-8-3373-5727-0.ch008>
- Kiros, H. W., & Chawla, A. S. (2025). Leadership Style and Service Quality on Customer Satisfaction: A Qualitative and Quantitative Exploration in Ethiopian Banks. In *SSRN Electronic Journal*. Elsevier BV. <https://doi.org/10.2139/ssrn.5067043>
- Lu, Y. (2023). Evaluation and Application of Public Management Service Quality of Smart City Based on Intelligent Computing. In *International Transactions on Electrical Energy Systems* (Vol. 2023, pp. 1–9). Wiley. <https://doi.org/10.1155/2023/6025958>
- Mitra, S., Sardar, P., & Chakraborty, S. (2025). Smart City. In *Global Encyclopedia of Public Administration, Public Policy, and Governance* (pp. 1–11). Springer Nature Switzerland. https://doi.org/10.1007/978-3-319-31816-5_4426-1
- Mustonen, M., Ameal, M., Ritmala, M., & Leino-Kilpi, H. (2024). Nursing Quality Indicators in Emergency Nursing. In *Journal of Nursing Care Quality* (Vol. 39, Number 4, pp. 376–382). Ovid Technologies (Wolters Kluwer Health). <https://doi.org/10.1097/ncq.0000000000000790>
- Nazarenko, V. A., & Ostroushko, B. P. (2024). SMART CITY MANAGEMENT SYSTEM UTILIZAING MICRO-SERVICES AND IOT-BASED SYSTEMS. In *Energy and automation* (Vol. 71, Number 1, pp. 29–38). National University of Life and Environmental Sciences of Ukraine. [https://doi.org/10.31548/energiya1\(71\).2024.029](https://doi.org/10.31548/energiya1(71).2024.029)
- Nozari, H., & Tavakkoli-Moghaddam, R. (2026). Optimization techniques for energy efficiency in the super-smart city. In *Energy-Efficient Transformative Technologies for Data-Driven Smart Cities* (pp. 91–106). Elsevier. <https://doi.org/10.1016/b978-0-443-27618-7.00014-5>
- Oorkavalan, G. B., Baddur, K., & Dange, V. R. (2025). AI Powered Smart Buildings with Automated Energy Optimization and Adaptive Facility Management Systems. In *IoT Architectures and AI-Enabled Smart City Solutions for Sustainable Urban Development* (pp. 394–423). RADemics Research Institute. <https://doi.org/10.71443/9789349552241-14>
- Oorkavalan, G. B., & Subramaniam, P. (2025). IoT Based Smart Waste Management and Automated Recycling Systems for Sustainable Urban Environments. In *IoT Architectures and AI-Enabled Smart City Solutions for Sustainable Urban Development* (pp. 253–282). RADemics Research Institute. <https://doi.org/10.71443/9789349552241-09>
- Öz, B., & Saygili, M. (2025). Trust Communication With Dentists, Perception of Service Quality, Patient Satisfaction in Dental Health Services. In *Journal of Dental Education*. Wiley. <https://doi.org/10.1002/jdd.13955>
- Putro, A. C. (2025). The Effect of Product Quality, Service Quality, Service Recovery on Customer Satisfaction and Customer Loyalty in Business to Customer (B2C), Case Study of AMA Group Bandung. In *International Journal of Current Science Research and Review*. Everant Journals. <https://doi.org/10.47191/ijcsrr/v8-i6-47>
- Rai, B., & Trivedi, R. (2024). Analysis on effects of mountain shadow on solar energy capacity at western slope of Gangtok city using Shadowmap 3D-GIS mapping tool. In *2024 Second International Conference on Smart Technologies for Power and Renewable Energy (SPECon)* (pp. 1–6). IEEE. <https://doi.org/10.1109/specon61254.2024.10537244>
- Rijayana, I. (2024). Influence of Service Quality, Price and Location on Customer Satisfaction. In *Adpebi Science Series* (Vol. 1, Number 1). Asosiasi Dosen Peneliti Ilmu Ekonomi dan Bisnis Indonesia. <https://doi.org/10.54099/icemat2023.v1i1.271>
- Rulianti, E., & Nurpribadi, G. (2024). The Effect of Public Service Quality, Work Discipline, and Organizational Culture on Community Satisfaction. In *Ilomata International Journal of Social Science* (Vol. 5, Number 1, pp. 60–74). Yayasan Sinergi Kawula Muda. <https://doi.org/10.52728/ijss.v5i1.1059>
- S., A. M., Aparna, G., & V., M. P. (2025). FPGA-based Real-Time Fault Suppression and Secure Smart Grid for Smart City Emulation. In *2025 5th International Conference on Soft Computing for Security Applications (ICSCSA)* (pp. 723–728). IEEE. <https://doi.org/10.1109/icscsa66339.2025.11171384>
- Saleha, D., Djuhrijjani, D., Awaliyah, R., Furqon, W., & Sudarmanto, E. (2025). Legal Analysis of Human Rights Protection within Smart City Policy Implementation in Indonesia. In *The Easta*

- Journal Law and Human Rights* (Vol. 4, Number 1, pp. 63–73). PT. Sanskara Karya Internasional. <https://doi.org/10.58812/eslhr.v4i01.778>
- Saputra, J. G. (2025). Assessing the Impact of Service Quality, Price, and Perceived Value on Customer Satisfaction: A Case Study of Jabodebek LRT at Jatimulya Station. In *Journal of Business, Management, and Social Studies* (Vol. 4, Number 2, pp. 97–111). Yayasan Appsikun Wedyatama Indonesia. <https://doi.org/10.53748/jbms.v4i2.98>
- Šekarić-Stojanović, N. (2024). Smart energy city as an urban energy problems' solution. In *Urbana bezbednost i urbani razvoj, Zbornik radova sa trece naucne konferencije - zbornik radova* (pp. 247–260). Univerzitet u Beogradu - Fakultet bezbednosti, Beograd
Univerzitet u Beogradu - Arhitektonski fakultet, Beograd. <https://doi.org/10.5937/ubur24247s>
- Selvaraj, R., Kuthadi, V. M., & Baskar, S. (2023). Smart building energy management and monitoring system based on artificial intelligence in smart city. In *Sustainable Energy Technologies and Assessments* (Vol. 56, p. 103090). Elsevier BV. <https://doi.org/10.1016/j.seta.2023.103090>
- Shi, J., Li, M., & Xu, Q. (2025). Leveraging AI and IoT for energy efficiency and power quality management in prefabricated smart buildings. In *Fourth International Conference on Intelligent Traffic Systems and Smart City (ITSSC 2024)* (p. 84). SPIE. <https://doi.org/10.1117/12.3050921>
- Sinaga, J. M., Hidayah, R. T., & Hendayani, R. (2025). The Influence of Mobile Service Quality, Perceived Service Quality and Price Fairness on GoFood Customer Loyalty in Bandung City Through Customer Satisfaction and Moderated by Personal Innovativeness: Generation Z's Case Study. In *Studies in Big Data* (pp. 55–70). Springer Nature Switzerland. https://doi.org/10.1007/978-3-031-75095-3_5
- Smith, V., Smith, A., & Carroll, L. (2025). Quality appraisal tools used in qualitative evidence syntheses of maternity care research: A scoping review. In *Midwifery* (Vol. 148, p. 104479). Elsevier BV. <https://doi.org/10.1016/j.midw.2025.104479>
- Stanković, J. J., Östh, J., & Marjanović, I. (2026). Benchmarking Local Government Smart City Initiatives: A Data Envelopment Analysis of European Urban Centers. In *Local and Urban Governance* (pp. 123–140). Springer Nature Switzerland. https://doi.org/10.1007/978-3-032-04265-1_7
- Supawanhar, S., Charilina, O., & Saputra, B. S. (2025). ANALISIS KEPUASAN PENGGUNAAN MOBILE JAMINAN KESEHATAN NASIONAL (JKN) PADA PASIEN PESERTA (BADAN PENYELENGGARA JAMINAN SOSIAL (BPJS) DI RUMAH SAKIT UMUM DAERAH BENGKULU TENGAH (SERVICE QUALITY). In *Journal of Governance and Public Administration* (Vol. 2, Number 3, pp. 596–604). Yayasan Nuraini Ibrahim Mandiri. <https://doi.org/10.70248/jogapa.v2i3.2099>
- Tietieriev, V. (2023). Transforming City Energy Management: Using Smart Grid Technologies for Improved Control and Energy Efficiency. In *Lighting Engineering & Power Engineering* (Vol. 62, Number 2, pp. 54–63). O.M.Beketov National University of Urban Economy in Kharkiv. <https://doi.org/10.33042/2079-424x.2023.62.2.03>
- Udo, S., Umoh, M., & Ewona, I. (2024). Evaluating the Impact of Renewable Energy Integration on Air Quality: A Study of Pollutant Reduction in an Urban city of Calabar. In *Trends in Renewable Energy* (Vol. 11, Number 1, pp. 24–51). Future Energy Service and Publishing. <https://doi.org/10.17737/tre.2025.11.1.00184>
- Utari, W., Indrawati, M., Sobakh, N., . W., & . R. (2024). The Effect of Service Quality, Consumer Perceptions, and Facilities on Consumer Satisfaction: Case study in Indonesia. In *Journal of Ecohumanism* (Vol. 3, Number 4, pp. 652–663). Creative Publishing House. <https://doi.org/10.62754/joe.v3i4.3465>
- Wang, L. (2024). Design industrial 5.1 air quality monitoring system and develop smart city infrastructure. In *Measurement: Sensors* (Vol. 35, p. 101292). Elsevier BV. <https://doi.org/10.1016/j.measen.2024.101292>
- Wang, X., & Ma, D. (2024). Smart city landscape architecture for sustainable urbanization in digital twin: Practical sustainable and reliable renewable based smart cities energy hub development. In *Sustainable Energy Technologies and Assessments* (Vol. 65, p. 103785). Elsevier BV. <https://doi.org/10.1016/j.seta.2024.103785>
- Wedy, Y. K., Pebrianti, W., & Listiana, E. (2025). The Influence of Service Quality, Information Quality, Trust and Customer Satisfaction on Customer Loyalty a Case Study at CU Tri Tapang

- Kasih. In *International Journal of Finance and Business Management* (Vol. 3, Number 1, pp. 1–12). PT Multitech Bintang Asia. <https://doi.org/10.59890/ijfbm.v3i1.177>
- Wu, H., & Yin, B. (2023). Research on the Turnout Monitoring System Based on Acceleration Sensors. In *2023 International Conference on Computer, Internet of Things and Smart City (CIoTSC)* (pp. 193–196). IEEE. <https://doi.org/10.1109/ciotsc60428.2023.00039>
- Yang, H., Zhang, S., Zeng, J., Tang, S., & Xiong, S. (2023). Future of sustainable renewable-based energy systems in smart city industry: Interruptible load scheduling perspective. In *Solar Energy* (Vol. 263, p. 111866). Elsevier BV. <https://doi.org/10.1016/j.solener.2023.111866>
- Yoe, P., Bastiaan, N. E., & Wiyono, A. E. (2024). The Impact of Service Quality, Employee Competency, and Digitalization on Patient Satisfaction at X Clinic. In *Indonesian Marketing Journal* (pp. 119–129). Universitas Pelita Harapan. <https://doi.org/10.19166/imj.v4i2.9763>
- Yuan, Z., & Yang, Y. (2025). Energy management strategy for extended-range electric vehicles based on adaptive ECMS with PI control. In *Fifth International Conference on Intelligent Traffic Systems and Smart City (ITSSC 2025)* (p. 55). SPIE. <https://doi.org/10.1117/12.3089316>
- Zhu, Y., & Yue, M. (2025). Design of an IoT-Based Smart City Energy Management System. In *2025 4th International Conference on Green Energy and Power Systems (ICGEPS)* (pp. 489–492). IEEE. <https://doi.org/10.1109/icgeps65133.2025.11034388>