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# Toward Secure, IoT-Enabled Adaptive Illumination in Smart Buildings: A Systematic Framework for Demand-Side Lighting Energy Management and Embedded Security Hardening in Developing Economies

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## Abstract

Artificial lighting represents one of the largest addressable components of building energy consumption in both developed and developing economies. In Sub-Saharan Africa, where chronic electricity supply deficits impose severe socioeconomic constraints, the optimization of demand-side lighting energy management constitutes a priority intervention. This paper presents a systematic conceptual and technological framework for the progressive evolution of sensor-based occupancy-driven illumination systems, from standalone Passive Infrared (PIR) microcontroller implementations toward fully IoT-enabled, adaptive, and predictive smart building lighting architectures, with embedded security hardening treated as a first-class design dimension rather than a downstream afterthought. Drawing on a structured review of fifteen empirical and theoretical studies published between 2010 and 2025, and grounded in empirical findings from a prototype PIR-Arduino implementation achieving 85% detection accuracy and an estimated 94% reduction in effective energy consumption, the paper characterizes the current state of the field, identifies six critical research gaps: stationary occupant insensitivity, offline operational resilience, multi-zone scalability, adaptive threshold learning, user acceptance in low-income settings, and security hardening across the connectivity and edge-intelligence tiers; and proposes a five-tier technology enhancement roadmap spanning from low-cost standalone deployment to edge-intelligence-enabled predictive control, with tier-specific security requirements specified at each connectivity transition. Quantitative demand-side management analyses across five building typologies demonstrate that occupancy-driven lighting automation could yield energy savings of 30–95% depending on space type and operational schedule. Because the proposed roadmap explicitly introduces wireless connectivity (Tier 4) and edge machine learning (Tier 5), the paper undertakes a structured security analysis of the architecture, identifying authentication, transport encryption, firmware integrity, and physical actuator access control as the principal hardening requirements that must accompany each connectivity transition; without these safeguards, the same IoT and MQTT-based mechanisms that enable remote monitoring and predictive control also expand the system's exposure to unauthorized access, sensor spoofing, and denial-of-service against building lighting infrastructure. The framework is specifically calibrated for developing-economy deployment contexts characterized by infrastructure constraints, cost sensitivity, and irregular electricity supply, offering a pragmatic, context-appropriate, and security-conscious pathway toward sustainable, intelligent building energy management.

**Keywords:** Smart Building, IoT-Enabled Lighting, Sensor Fusion, Energy Conservation, Developing Economies, Smart City

## 1. Introduction

The convergence of sensor technology, wireless communication, embedded computing, and cloud analytics has created unprecedented opportunities for transforming passive, static building energy systems into dynamically adaptive, data-driven infrastructure. Nowhere is this transformation more immediately impactful than in building lighting systems, which account for 15–19% of global electrical energy consumption and represent a disproportionately large fraction of avoidable energy waste in both residential and commercial building stocks (Fernandez & Mideros, 2018; Bachanek *et al*., 2021) [8, 6]. The central insight driving the field is deceptively simple: a luminaire that is illuminated in an unoccupied space produces no useful work, and the elimination or reduction of such waste through occupancy-responsive automation constitutes one of the most cost-effective demand-side energy management strategies available without requiring changes to energy supply infrastructure. The same convergence of technologies that enables this opportunity, however, also introduces a parallel and frequently underexamined liability: as lighting control infrastructure becomes networked, sensor-driven, and remotely addressable, it inherits the security exposure characteristic of IoT systems more broadly, a dimension this paper treats with the same rigor applied to energy performance.

In the context of developing economies in Sub-Saharan Africa in particular, this opportunity assumes additional urgency. Nigeria, for instance, operates with a national electricity grid that consistently fails to meet aggregate demand, with per-capita electricity consumption among the lowest in the world despite a population exceeding 200 million (Obioma *et al*., 2025) [15]. Within this context, the reduction of unnecessary consumption at the point of use is not merely an environmental preference but a functional necessity for households and institutions that cannot rely on continuous power availability. For these settings, the deployment of automated lighting systems that respond to real-time occupancy without requiring ongoing connectivity to cloud infrastructure represents a both technically and economically rational intervention, provided that any subsequent extension toward connectivity is undertaken with deliberate attention to the authentication, encryption, and access-control mechanisms that resource-constrained deployments are otherwise prone to omit.

The intellectual lineage of occupancy-responsive lighting extends from early motion sensor applications in security and access control through to contemporary smart building systems integrating machine learning, Internet of Things (IoT) platforms, and urban data infrastructure. However, despite substantial research activity across this spectrum, a coherent framework that maps the landscape of available technologies to the specific requirements, constraints, and security implications of developing-economy deployment has not been systematically articulated. This paper addresses that gap by: (i) reviewing the current state of occupancy-sensing and smart lighting technology; (ii) identifying critical research gaps, including security hardening; (iii) presenting empirical findings from a prototype PIR-based implementation; (iv) proposing a structured five-tier technology enhancement roadmap calibrated to the resource constraints and infrastructure realities of developing-economy deployment contexts; and (v) specifying the security requirements that must accompany each tier's connectivity and intelligence enhancements.

### 1.1 Scope and Objectives

The present paper pursues five principal objectives:

1. To provide a structured synthesis of the smart lighting literature with particular attention to sensor modalities, IoT architectures, and energy management strategies;
2. To present quantitative demand-side management analyses characterizing the energy saving potential of occupancy-driven lighting across representative building typologies;
3. To synthesize empirical prototype findings within the broader technology landscape and identify residual performance gaps;
4. To propose an evidence-based technology enhancement roadmap for progressive system evolution toward fully adaptive smart building lighting;
5. To identify the security requirements including authentication, transport encryption, firmware integrity, and actuator access control, that must accompany each stage of the proposed roadmap, particularly the transition to networked (Tier 4) and edge-intelligence (Tier 5) configurations.

## 2. Theoretical and Analytical Framework

### 2.1 Demand-Side Energy Management Theory

Demand-side management (DSM) theory provides the analytical foundation for evaluating the impact of occupancy-responsive lighting. DSM encompasses the suite of interventions including technological, behavioral, regulatory and economic, that reduce energy consumption at the point of use, as distinct from supply-side strategies that seek to increase generation capacity. In the context of building lighting, DSM theory distinguishes between: (i) efficiency interventions, which reduce the power rating of the lighting technology (e.g., lamp substitution from incandescent to LED); (ii) control interventions, which reduce the active illumination duration by matching light output to actual demand; and (iii) integrated interventions, which combine efficiency and control to achieve multiplicative savings (Jin *et al*., 2020; Cheng *et al*., 2020) [10, 7].

The theoretical maximum energy saving achievable through occupancy-driven control alone is bounded by the occupancy factor Focc, defined as the ratio of occupied to total available hours:

$$F_{occ} = \mathbf{t_{occupied}} \ / \ \mathbf{T_{tota}} \qquad (1)$$

The potential energy saving through control is then:

$$\mathbf{E_{saving(control)}} = \mathbf{P_{lamp}} \times \mathbf{(1} - F_{occ}\mathbf{)} \times \mathbf{T_{total}} \qquad (2)$$

For combined efficiency and control interventions, the total energy saving relative to a manual incandescent baseline is:

$$\mathbf{E_{saving(total)}} = \mathbf{T_{total}} \times \mathbf{(P_{inc}} - \mathbf{P_{LED}} \times F_{occ}\mathbf{)} \qquad (3)$$

Where $P_{inc}$ is the rated power of the incumbent incandescent lamp (W) and $P_{LED}$ is the rated power of the LED replacement (W). This formulation makes explicit the interaction between lamp efficiency and control duration: a higher-efficiency lamp alone does not eliminate waste during unoccupied periods, and control alone without lamp efficiency improvement foregoes a substantial fraction of the achievable saving. The empirical data presented in Section 4 demonstrate the practical magnitude of these interactions across representative building types.

## 2.2 IoT Architecture for Smart Lighting Systems

Internet of Things (IoT) architectures for smart lighting systems are conventionally organized into four functional layers: Perception, Connectivity, Processing/Edge, and Application/Cloud. Each layer introduces specific technological options, performance characteristics, and infrastructure requirements that must be matched to the deployment context; each layer also introduces a distinct category of security exposure, summarized alongside its functional characterization in Table 1.

**Table 1:** IoT Architecture Layers for Smart Lighting: Technologies, Functions, Constraints, and Security Exposure

| IoT Layer | Technology / Protocol | Function | Limitation in Constrained Contexts | Principal Security Exposure |
|---|---|---|---|---|
| Perception | PIR / Ultrasonic / Microwave Sensors | Occupancy detection and environmental sensing | Single modality limits stationary occupant detection | Physical spoofing/evasion of sensor signal |
| Connectivity | Wi-Fi (IEEE 802.11b/g/n), Zigbee, MQTT | Data transmission between sensor node and broker | Dependence on stable infrastructure | Unencrypted/unauthenticated message channels |
| Processing | Microcontroller (Arduino, ESP32, NodeMCU) | Real-time signal processing and state control | Limited computational resources for ML inference | Unauthenticated firmware/OTA update paths |
| Cloud / Edge | AWS IoT Core, Azure IoT Hub, Edge nodes | Data aggregation, analytics, remote management | Latency, cost, connectivity requirements | Credential/API key exposure; data-at-rest leakage |
| Application | Mobile app, Web dashboard, SCADA | User interface and control panel | Requires user training and digital literacy | Weak access control; session hijacking |

A critical architectural decision in developing-economy contexts concerns the balance between cloud-dependent and edge-resident processing. Cloud-dependent architectures offer virtually unlimited analytical capacity and enable sophisticated multi-site data integration, but introduce vulnerability to network interruption that may be unacceptable in environments where internet connectivity is intermittent or expensive, and additionally introduce a remote attack surface absent from purely local deployments. Edge-resident architectures, where control logic, state management, and adaptive algorithms are executed locally on the MCU or a co-located edge processor, sacrifice analytical breadth but provide operational continuity independent of network availability, while also confining the consequences of any single compromised node to a smaller blast radius (Li *et al*., 2023; Omar *et al*., 2022) [11, 16]. The architecture proposed in Section 5 explicitly addresses this trade-off through a hybrid approach, paired with the tier-specific security controls detailed in Section 2.4 and Section 5.

## 2.3 Sensor Technology Landscape

The sensing subsystem constitutes the foundational element of any occupancy-driven lighting system, and the selection of sensor modality exerts a decisive influence on detection accuracy, power consumption, deployment cost, and environmental robustness. Table 2 provides a comparative characterization of the principal sensor modalities employed in the smart lighting literature.

**Table 2:** Comparative Analysis of Occupancy Sensor Modalities for Lighting Control Applications

| Sensor Type | Detection Principle | Range (m) | Power (mW) | Advantages | Limitations |
|---|---|---|---|---|---|
| PIR (Passive IR) | Infrared differential | 3–12 | < 1 | Low cost, passive, low power | LOS-dependent; stationary-blind; spoofable by shielding |
| Ultrasonic | Sound wave reflection | 2–8 | 15–40 | Detects stationary objects | Sensitive to air currents; audible noise |
| Microwave Doppler | RF wave reflection | 5–30 | 20–100 | Penetrates materials; wide range | High cost; false triggers; RF jamming susceptibility |
| Camera / Vision | Image processing | 3–15 | 200–1000 | Rich contextual data; identity-capable | Privacy concerns; high compute demand; sensitive data handling |
| Capacitive | Electric field disturbance | 0.1–2 | 5–20 | No LOS required; compact | Very short range; temperature-sensitive |

The PIR sensor, as employed in the prototype implementation described in Section 4, occupies the lowest-cost, lowest-power position in this taxonomy, making it the most pragmatically appropriate choice for single-zone standalone deployment in resource-constrained contexts. However, its fundamental limitation includes insensitivity to stationary occupants arising from the differential detection principle, constrains its performance in occupancy scenarios where individuals remain stationary for extended periods, such as reading, desk work, or meeting attendance (Amuta *et al*., 2024; Jia, 2024) [1, 9]. This same limitation, noted in Table 2, also constitutes the sensor's primary evasion vector from a security standpoint. Sensor fusion architectures, combining PIR with ultrasonic or microwave Doppler modalities, offer a practical path to addressing this limitation while maintaining acceptable cost and power budgets and additionally raise the bar for evasion by requiring an adversary to simultaneously defeat multiple, physically distinct detection principles.

## 2.4 IoT Security and Privacy Considerations for Lighting Infrastructure

As the IoT architecture characterized in Section 2.2 progresses from Perception toward Application/Cloud layers, it accumulates security obligations that are frequently underweighted relative to functional and energy-performance criteria in the smart lighting literature. Sicari *et al*. (2015) [18] catalogued the recurring deficiencies of IoT deployments which are unauthenticated firmware update paths, absent transport-layer encryption, weak device authentication and insufficient access control over physical actuators, all of which are directly applicable to the

Connectivity and Processing layers of Table 1. Atzori *et al.* (2010) [5] further observed that the interconnection of heterogeneous, resource-constrained devices systematically magnifies the consequences of weak per-device security postures, a dynamic of particular relevance to the multi-zone, mesh-networked deployments proposed for Tier 4 and Tier 5 in Section 5. Omar *et al.* (2022) [16], in their survey of IoT-based street lighting architectures, similarly identified unsecured remote-control channels, the absence of standardized security benchmarking, and inadequate authentication of control commands as persistent weaknesses across deployed lighting networks employing Zigbee, Z-Wave, LoRaWAN, and NB-IoT protocols.

Three categories of security obligation are particularly salient to the roadmap developed in this paper. First, transport-layer security: MQTT, the publish-subscribe protocol identified in Table 1 as the primary Connectivity-layer mechanism for Tier 4 deployments, transmits messages in plaintext by default and requires explicit configuration of TLS and broker-level authentication (username/password or certificate-based) to prevent eavesdropping on occupancy telemetry or injection of spoofed control commands. Second, firmware and over-the-air (OTA) update integrity: the ESP8266/ESP32 modules proposed for Tier 4 and Tier 5 support OTA firmware updates, a capability that materially improves maintainability but, absent cryptographic signature verification, also introduces a remote firmware-injection vector unavailable to the standalone Tier 1 architecture. Third, physical actuator access control: as the relay or PWM dimming output (Section 5) becomes addressable via the cloud dashboard or mobile application identified in Table 1, unauthorized access to that interface through weak credentials, session hijacking, or exposed API keys. This translates directly into unauthorized control of physical lighting infrastructure, with denial-of-service (forced disablement) and nuisance-switching as the principal consequences. These obligations are mapped explicitly onto the five-tier roadmap in Section 5, where each connectivity-introducing tier is paired with a corresponding minimum security baseline.

## 3. Critical Review of the Smart Lighting Literature

### 3.1 Energy Efficiency Foundations (2010–2018)

The scholarly foundation of the smart lighting field was established by Muhamad *et al.* (2010) [14], who articulated the fundamental principles of energy-efficient lighting design for buildings, encompassing luminaire selection, zoning strategies, and daylight harvesting. This contribution, while predating the proliferation of IoT-enabled sensing and control, established the performance benchmarks and analytical vocabulary against which subsequent technological innovations have been evaluated. The work of Fernandez and Mideros (2018) [8] extended this foundation by conducting a comparative evaluation of lighting control techniques for sustainable buildings, providing a structured taxonomy of dimming, occupancy and daylight sensing strategies that remains a useful conceptual reference despite the absence of intelligent automation, IoT integration or security considerations in the evaluated systems.

These foundational contributions collectively establish that energy-efficient lighting requires not merely the substitution of efficient lamp technologies but the implementation of control strategies that match illumination to actual occupancy and daylight availability. This is a principle that subsequent IoT-oriented research has sought to operationalize through increasingly sophisticated and increasingly network-exposed, technological means.

### 3.2 Motion Sensor-Based Implementations (2017–2025)

The dominant approach to occupancy-responsive lighting automation in the cost-constrained segment of the market has been the integration of PIR sensors with microcontroller-based switching logic. Amuta *et al.* (2024) [1] demonstrated measurable energy savings through PIR-based activation in built environments, reporting detection accuracy in the range of 80–84% across varied indoor test conditions. Sulaiman *et al.* (2024) [19] and Argelwar *et al.* (2024) [3] similarly reported effective single-zone implementations, with the latter explicitly targeting low-cost deployment in commercial buildings. Obioma *et al.* (2025) [15] extended this work toward improved reliability and responsiveness, achieving sub-second response times comparable to those reported in the present study. Arun and Gopan (2025) [4] examined relay-based load switching for low-voltage microcontroller-driven lighting from a design-safety perspective, providing engineering guidance directly relevant to the actuation-layer hardening discussed in Section 5, though without extending the analysis to unauthorized or remote actuation scenarios.

A persistent theme across these contributions is the explicit acknowledgment of PIR's stationary occupant insensitivity as the principal performance limitation, without, however, proposing integrated solutions that address this limitation within the low-cost deployment constraint, and without examining the security implications of the architectures described. The present framework explicitly addresses the detection gap through the Tier 2 sensor fusion pathway described in Section 5, and the security gap through the layer-specific hardening requirements introduced in Section 2.4.

### 3.3 IoT-Integrated and Connected Architectures (2020–2024)

A substantial body of research has explored the performance enhancements achievable through IoT integration. Li *et al.* (2023) [11] demonstrated that connectivity substantially improves system responsiveness and administrative oversight, enabling remote activation, real-time monitoring and centralized data collection, capabilities that, as noted in Section 2.4, simultaneously expand the system's exposure to unauthorized remote control absent corresponding authentication safeguards. Jia (2024) [9] advanced the capability frontier through multi-sensor fusion, combining occupancy, ambient light and environmental sensing to enable context-aware adaptive responses that single-modality PIR systems cannot achieve. Cheng *et al.* (2020) [7] proposed a distributed wireless sensor network architecture that improves system fault tolerance at the cost of increased latency and, as the authors themselves acknowledge, increased security complexity.

Omar *et al.* (2022) [16] conducted a comprehensive survey of IoT-based street lighting architectures, cataloguing the diversity of communication protocols including Zigbee, Z-Wave, LoRaWAN and NB-IoT, and noting the absence of standardized benchmarking frameworks that would enable definitive performance comparisons; their survey also flagged inconsistent security practice across surveyed deployments as a barrier to safe scaling. Micko *et al.* (2023) [13] complemented this survey with a taxonomic review of IoT sensor systems for road infrastructure monitoring, highlighting the importance of robust connectivity and redundant communication pathways in safety-critical outdoor applications, where compromised sensing or actuation carries direct public-safety consequences.

### 3.4 Predictive and Intelligent Control

The most technically sophisticated contribution in the reviewed literature is the work of Jin *et al.* (2020) [10], who applied data-driven model predictive control (MPC) to building lighting systems using historical occupancy data. By constructing probabilistic occupancy models from time-series sensor data and incorporating these predictions into an optimization-based control framework, the MPC approach achieves energy savings superior to reactive occupancy control by anticipating periods of vacancy and proactively adjusting lighting states. This approach represents the current performance frontier in smart lighting control, achieving accuracy rates of approximately 95% and energy savings substantially exceeding those achievable through simple threshold-based PIR switching.

However, the MPC approach introduces substantial requirements for data infrastructure, computational resources, and model maintenance that place it well beyond the deployment envelope appropriate for low-cost, infrastructure-constrained settings; it also introduces a data-governance dimension, since historical occupancy data is itself sensitive telemetry whose storage and transmission require access control. The Tier 5 proposal in Section 5 represents a pragmatic adaptation of this paradigm through the application of lightweight edge-resident machine learning (TinyML), which brings predictive capability within the resource budget of modern IoT microcontrollers such as the Arduino Nano 33 BLE Sense or ESP32, while keeping the bulk of occupancy data resident at the edge rather than centralized in the cloud.

### 3.5 User-Centered and Sociotechnical Dimensions

Tongsubanan and Kasemsarn (2024) [20] contribute a complementary sociotechnical perspective by applying user-centered design (UCD) principles to the development of energy-saving applications. Their findings emphasize that technical performance is a necessary but insufficient condition for effective adoption; system usability, interface accessibility, and alignment with user mental models are equally determinative of real-world impact. This perspective is particularly significant in developing-economy contexts, where digital literacy varies widely and user trust in automated systems may be limited by prior experience with unreliable technology a trust that is further eroded by security incidents such as unauthorized remote control of household lighting. The enhancement roadmap proposed in Section 5 incorporates UCD considerations, including comprehensible security prompts (e.g., default-password change enforcement), as a horizontal design principle across all tiers, not merely as an afterthought in the final implementation stage.

### 3.6 Identified Research Gaps

The structured review reveals six critical gaps that remain inadequately addressed in the extant literature and that represent the highest-priority directions for future research investment. These gaps and proposed pathways are summarized in Table 3.

**Table 3:** Critical Research Gaps in Occupancy-Driven Smart Lighting and Proposed Pathways

| Research Gap | Representative Studies Noting Gap | Proposed Pathway |
|---|---|---|
| Stationary occupant detection | Amuta *et al.* (2024) [1]; Jia (2024) [9] | Sensor fusion: PIR + ultrasonic or microwave Doppler modality |
| Offline operational resilience | Li *et al.* (2023) [11]; Cheng *et al.* (2020) [7] | Hybrid edge-cloud architecture with local fallback state machine |
| Scalability to multi-zone buildings | Mahoor *et al.* (2017) [12]; Omar *et al.* (2022) [16] | Mesh network topology with hierarchical MCU coordination |
| Adaptive threshold learning | Jin *et al.* (2020) [10] | On-device lightweight ML (TinyML) trained on occupancy time-series |
| User acceptance in low-income settings | Tongsubanan & Kasemsarn (2024) [20] | Participatory design methodology with end-user co-design cycles |
| Security hardening across connectivity and edge-intelligence tiers | Sicari *et al.* (2015) [18]; Omar *et al.* (2022) [16]; Atzori *et al.* (2010) [5] | Tier-specific authentication, transport encryption, signed OTA updates, and actuator access control (Sections 2.4, 5) |

## 4. Empirical Analysis: Energy Saving Potential Across Building Typologies

### 4.1 Analytical Methodology

To contextualize the energy saving potential of occupancy-driven lighting control at a sector scale, a quantitative demand-side management analysis was conducted across five representative building typologies. For each typology, the occupancy ratio (Focc) was estimated from published activity schedule data, and the energy saving achievable through occupancy-responsive control was computed using Equations (1)–(3) from Section 2.1. The analysis assumes a baseline scenario employing 60 W incandescent luminaires operated under manual control, and a target scenario employing 9 W LED luminaires under motion-responsive control. Both scenarios assume an equivalent illumination output, consistent with the typical luminous efficacy advantage of LED over incandescent technology (approximately 80–110 lm/W versus 10–15 lm/W, respectively).

### 4.2 Results

**Table 4:** Demand-Side Energy Saving Analysis Across Building Typologies

| Building Type | Avg. Occupancy Ratio (%) | Lighting Fraction of Energy (%) | Estimated DSM Saving (%) |
|---|---|---|---|
| Classroom (8 h school day) | 45–60 | 30–40 | 40–55 |
| Office (8 h workday) | 50–70 | 25–35 | 30–50 |
| Hospital Corridor (24 h) | 20–35 | 35–50 | 65–80 |
| Residential Bathroom | 5–15 | 10–20 | 85–95 |
| Parking Structure (24 h) | 10–25 | 40–60 | 75–90 |

The results demonstrate that occupancy-driven control delivers the greatest relative energy savings in space types with low occupancy ratios and high lighting energy fractions like parking structures, residential bathrooms, and hospital corridors, where automatic deactivation eliminates sustained illumination of spaces that are unoccupied for 65–95% of their operational period. Classrooms and offices yield more moderate savings, reflecting higher average occupancy ratios, but remain significant given the absolute volume of electrical energy consumed across these space types in a national building stock. The energy saving estimates assume perfect sensor performance (no missed detections or false triggers); the 85% detection accuracy reported for the prototype implementation would modestly reduce these figures, primarily through occasional phantom activations that extend the effective illumination duration. It is also noted that hospital corridors and parking structures. Precisely the typologies with the highest projected DSM savings, are also the typologies in which unauthorized actuation (Section 2.4) carries the most significant safety consequence, reinforcing the case for prioritizing actuator access control in exactly the deployment contexts offering the greatest energy upside.

### 4.3 Carbon Abatement Implications

At the Nigerian national grid emission factor of approximately 0.55 kg $CO_2$ per kWh, the energy savings quantified above translate into meaningful per-luminaire carbon abatement contributions. For a single residential bathroom luminaire achieving a 94% energy saving relative to the manual incandescent baseline—as demonstrated by the prototype system—the annual $CO_2$ emission reduction is:

$$\Delta CO_2 = \Delta E \times EF = 8.55\ kWh/yr \times 0.55\ kg/kWh \approx 4.70\ kg\ CO_2/yr \quad (4)$$

While modest at the individual luminaire scale, this figure scales linearly across the installed base. With an estimated 50 million indoor luminaires in Nigeria's residential and institutional building stock, widespread adoption of occupancy-responsive LED lighting could theoretically contribute a cumulative abatement of approximately 235,000 tonnes of $CO_2$ per annum—a meaningful contribution to national climate commitments under the Paris Agreement framework.

### 4.4 Figure: IoT System Architecture Diagram

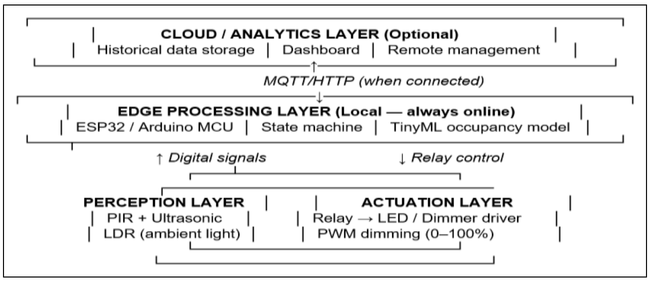

**Fig 1:** Proposed IoT-Enabled Smart Lighting System Architecture (Hybrid Edge-Cloud, with Security Control Points)

## 5. Five-Tier Technology Enhancement Roadmap

### 5.1 Framework Overview

The five-tier enhancement roadmap presented in this section operationalizes the theoretical framework and empirical findings into a structured upgrade pathway that organizations and institutions can follow to progressively enhance the capability, intelligence, and energy performance of their lighting infrastructure. Each tier is defined by a specific combination of sensing, processing, connectivity, and analytics capabilities, with explicit cost category designations, performance expectations, infrastructure prerequisites, and consistent with the security framework developed in Section 2.4 a minimum security baseline calibrated to developing-economy deployment contexts.

The roadmap is designed to be incrementally adoptable: each tier builds directly on the hardware and firmware of the preceding tier, enabling organizations to stage their investment over time as budgets permit and as evidence from lower-tier deployment builds institutional confidence in the technology. This incremental architecture also mitigates the risk of technological lock-in by ensuring that each tier delivers standalone value independently of subsequent upgrades. Critically, the security baseline at each tier is treated as non-optional rather than as a premium add-on: the roadmap is structured so that no tier introduces a new connectivity or remote-control capability without a corresponding minimum security control, summarized in Table 6.

**Table 5:** Five-Tier Technology Enhancement Roadmap for Occupancy-Driven Smart Lighting

| Enhancement Tier | Technology Added | Cost Category | Expected Accuracy / Saving | Prerequisite Infrastructure |
|---|---|---|---|---|
| Tier 1 (Baseline) | PIR + MCU + Relay | Very Low | ~85% accuracy; ~94% energy saving | None — standalone |
| Tier 2 (Multi-sensor) | PIR + Ultrasonic fusion | Low | ~91–93% accuracy; ~94% saving | Additional sensor pin |
| Tier 3 (Ambient-adaptive) | PIR + LDR + Daylight harvesting | Low–Medium | ~91% accuracy; >95% saving | Analog input; LDR module |
| Tier 4 (IoT-connected) | ESP8266/ESP32 + MQTT + Dashboard | Medium | ~93–95% accuracy; advanced analytics | Wi-Fi or cellular network |
| Tier 5 (AI-predictive) | Edge ML + Historical data + MPC | High | >95% accuracy; optimized pre-emptive control | Edge processor; data storage |

**Table 6:** Minimum Security Baseline by Enhancement Tier

| Enhancement Tier | New Attack Surface Introduced | Minimum Security Baseline |
|---|---|---|
| Tier 1 (Baseline) | Physical access to exposed serial/programming port | Fuse-bit locking or physical enclosure restricting programming access |
| Tier 2 (Multi-sensor) | None beyond Tier 1 (additional sensor remains local) | Carried forward from Tier 1 |
| Tier 3 (Ambient-adaptive) | None beyond Tier 1 (LDR input remains local, PWM output local) | Carried forward from Tier 1 |
| Tier 4 (IoT-connected) | Wi-Fi/MQTT network exposure; dashboard remote access | TLS-encrypted MQTT with broker authentication; unique per-device credentials; authenticated dashboard access; default-credential change enforced at first boot |
| Tier 5 (AI-predictive) | OTA firmware updates; centralized historical occupancy data | Cryptographically signed OTA updates; encrypted at-rest storage of occupancy time-series; data minimization/aggregation prior to cloud transmission |

### 5.2 Tier 1: Standalone PIR-Microcontroller (Baseline)

The Tier 1 implementation corresponds to the prototype system described in the companion study (Aremu, 2025) [2], comprising an HC-SR501 PIR sensor interfaced with an Arduino Uno microcontroller via direct digital input, with relay-based load switching and a 12-second configurable inactivity timeout. This configuration achieves an estimated detection accuracy of 85% and energy savings of approximately 94% relative to the manual incandescent baseline, at a component cost accessible to individual households and small institutions in Nigeria. The Tier 1 system requires no network infrastructure and is fully operational without any external connectivity, making it the most robust deployment option for environments with unreliable electricity and communications infrastructure; its security profile, accordingly, is dominated by physical rather than network exposure, and is adequately addressed through restriction of physical access to the programming interface, as detailed in the companion paper's threat-modeling analysis (Aremu, 2025) [2].

### 5.3 Tier 2: PIR–Ultrasonic Sensor Fusion

The primary limitation of Tier 1 is the PIR sensor's insensitivity to stationary occupants. Tier 2 addresses this through the co-deployment of an HC-SR04 ultrasonic distance sensor, which detects the presence of stationary objects including seated or standing human occupants through the reflection of 40 kHz acoustic pulses. The fused detection logic applies a logical OR criterion: the relay is maintained in the energized state if either the PIR sensor reports motion or the ultrasonic sensor reports an object within a defined presence distance threshold. The detection accuracy improvement achievable through this fusion approach is estimated at 6–8 percentage points based on sensor characterization data reported in the literature (Jia, 2024) [9]. The combined power consumption of the PIR and ultrasonic subsystems remains below 50 mW, well within the budget of a standard 5V USB supply. As both sensing modalities remain locally wired to the MCU with no network exposure introduced, Tier 2 inherits the Tier 1 security baseline unchanged, while incidentally raising the practical difficulty of sensor evasion by requiring simultaneous defeat of two physically distinct detection principles.

### 5.4 Tier 3: Ambient-Adaptive Illumination

Tier 3 introduces a Light Dependent Resistor (LDR) to the sensing subsystem, enabling the system to suppress lighting activation during periods when ambient natural illumination is sufficient to meet occupant needs without artificial augmentation. The LDR output is read through an analog input pin of the Arduino and compared against a configurable illuminance threshold, expressed as an analog voltage value. The modified control logic suppresses relay activation even in the presence of PIR-detected motion if the measured ambient light level exceeds the threshold. This daylight harvesting function can reduce effective illumination duration by an additional 15–30% in spaces with adequate fenestration, extending total energy savings beyond the 94% baseline achieved at Tier 1 (Fernandez & Mideros, 2018) [8]. A PWM dimming output, replacing the binary relay, enables continuous illuminance control that further reduces energy consumption during partial daylight conditions; as with Tier 2, this enhancement remains entirely local and introduces no new network-facing security exposure beyond the Tier 1 baseline.

### 5.5 Tier 4: IoT-Connected Monitoring and Remote Control

Tier 4 extends the system to network connectivity through the substitution of the Arduino Uno with an ESP8266 or ESP32 microcontroller module, which integrates a Wi-Fi transceiver alongside the MCU core. The system communicates occupancy events, energy consumption estimates, and system status to a cloud-hosted MQTT broker, from which a web-based or mobile dashboard enables real-time monitoring and remote configuration. The Tier 4 firmware implements a hybrid architecture in which all primary sensing and switching logic continues to execute at the edge, ensuring uninterrupted local operation during network outages, while data aggregation, historical analytics, and remote override commands are mediated through the cloud connection when available. This architecture directly addresses the offline resilience gap identified in Section 3.6. Because Tier 4 is the first stage in the roadmap to introduce a network-addressable control surface, it is also the first stage at which the security baseline of Table 6 becomes mandatory rather than precautionary: MQTT traffic must be TLS-encrypted and broker-authenticated, each deployed device must carry a unique credential rather than a shared default, and the dashboard's remote-override capability must itself be access-controlled, since an unauthenticated or weakly authenticated override channel would directly negate the offline-resilience benefit by exposing the relay to remote unauthorized actuation whenever connectivity is available.

### 5.6 Tier 5: Edge-AI Predictive Control

Tier 5 represents the integration of lightweight machine learning inference at the edge using TinyML frameworks, specifically TensorFlow Lite for Microcontrollers, to enable predictive occupancy control. A time-series occupancy model trained on historical PIR activation data collected through the Tier 4 logging infrastructure is quantized and deployed on the ESP32's Xtensa LX6 dual-core processor, which provides sufficient computational capacity for inference on models of moderate complexity. The predictive model generates probability-of-occupancy estimates for each 15-minute slot of the day, enabling the system to pre-emptively activate lighting in anticipation of regular occupancy patterns, eliminating the activation latency inherent in purely reactive systems while also extending the inactivity timeout during periods of historically low occupancy probability. This approach approximates the model predictive control paradigm of Jin *et al.* (2020) [10] within the resource and cost constraints of an affordable embedded platform. Tier 5 introduces two additional security obligations beyond those of Tier 4: the OTA mechanism used to deploy updated occupancy models to fielded devices must employ cryptographic signature verification to prevent malicious model or firmware substitution, and the historical occupancy time-series—which constitutes a detailed behavioral record of when a space is occupied or vacant—must be protected through encrypted storage and data-minimization practices, given its sensitivity as an indicator of household or institutional activity patterns.

## 6. Implications for Policy, Practice, and Research

### 6.1 Policy Implications

The findings of this study carry several important implications for energy policy in developing economies. The demonstrated accessibility and effectiveness of Tier 1 implementations suggests that building energy codes and standards for new construction in Nigeria and comparable economies should mandate occupancy-responsive lighting in specified space types: corridors, restrooms, parking structures, and non-continuous-occupancy offices as a minimum performance requirement. Such mandates could be implemented at minimal additional construction cost relative to the total building budget, while delivering energy savings that materially improve building operational economics and reduce the peak demand burden on constrained national grids. Incentive mechanisms including subsidized component procurement programs, utility rebate schemes, or tax incentives for certified smart lighting installations could accelerate adoption in the existing building stock beyond new construction. Where such mandates extend to networked (Tier 4/5) installations, policy frameworks should additionally specify minimum cybersecurity baselines consistent with Table 6 as a condition of certification, to prevent subsidized adoption from inadvertently expanding an insecure installed base.

### 6.2 Practical Deployment Guidance

For practitioners seeking to deploy occupancy-responsive lighting systems in developing-economy contexts, several practical considerations emerge from the present analysis. First, sensor placement significantly influences detection accuracy: mounting height of 0.6–0.9 m with unobstructed horizontal coverage optimizes the PIR sensor's detection footprint relative to occupant movement planes. Second, the inactivity timeout should be calibrated to the specific use case: the 12-second prototype setting is appropriate for high-traffic corridors but may be inappropriately short for offices or classrooms where brief stationary periods do not indicate departure. Third, for deployments in spaces with significant obstacle density or irregular geometry, Tier 2 sensor fusion should be adopted as the minimum configuration. Fourth, the relay module selection should account for the mains voltage and current rating of the lighting circuit to ensure safe and durable operation (Arun & Gopan, 2025) [4]. Fifth, any deployment that introduces Wi-Fi or MQTT connectivity (Tier 4 and above) should not be commissioned with manufacturer-default credentials, and should verify TLS configuration on the MQTT broker connection prior to field rollout, as these two omissions account for the majority of documented unauthorized-access incidents in comparable IoT lighting deployments (Omar *et al.*, 2022) [16].

### 6.3 Research Priorities

This analysis identifies six priority research directions that would most significantly advance the field: (i) development and open-source publication of validated lightweight occupancy models suitable for TinyML deployment on resource-constrained MCU platforms; (ii) empirical evaluation of sensor fusion architectures, particularly PIR-ultrasonic and PIR-microwave Doppler combinations, under controlled and naturalistic occupancy conditions; (iii) field trials of hybrid edge-cloud architectures in developing-economy building stock to characterize real-world offline resilience and energy performance; (iv) longitudinal user studies in low-income and low-digital-literacy settings to characterize adoption barriers and design appropriate intervention strategies; (v) development of standardized benchmarking protocols enabling cross-study comparison of smart lighting system performance across sensor modalities, control architectures, and building typologies; and (vi) empirical penetration-testing studies of fielded Tier 4/5 smart lighting deployments to validate, under real-world conditions, the theoretical security baseline proposed in Table 6 and to quantify the prevalence of common misconfigurations such as default credentials and unencrypted MQTT channels.

## 7. Conclusion

This paper has presented a systematic framework for understanding and advancing the state of occupancy-driven lighting energy management systems, with particular attention to the requirements, constraints, and security implications of developing-economy deployment contexts. Building on a structured review of fifteen studies spanning the years 2010–2025, empirical findings from a prototype PIR-Arduino implementation, and quantitative DSM analyses across five building typologies, the paper has demonstrated that occupancy-responsive lighting automation is technically mature, cost-accessible, and capable of delivering substantial and immediate energy savings across a wide range of building types.

The proposed five-tier enhancement roadmap provides a practical, evidence-based, and security-conscious upgrade pathway from standalone PIR-microcontroller baseline systems accessible to individual households and small institutions at minimal cost, through IoT-connected architectures offering remote monitoring and data-driven optimization, to edge-intelligence-enabled predictive control systems capable of approaching the performance ceiling of centralized model predictive control within the constraints of affordable embedded hardware. The framework is explicitly designed for incremental adoption, ensuring that each tier delivers standalone value while preserving compatibility with subsequent upgrades, and ensuring that no tier introduces new connectivity or remote-control capability without a commensurate minimum security baseline.

Critical research gaps including stationary occupant insensitivity, offline operational resilience, multi-zone scalability, adaptive threshold learning, user acceptance in low-income settings, and security hardening across the connectivity and edge-intelligence tiers have been identified and mapped to concrete technological and methodological pathways. Addressing these gaps through focused empirical research will be essential to realizing the full potential of smart lighting as a demand-side energy management strategy at urban and national scale in developing economies, without that potential being undermined by preventable security incidents as networked adoption scales. The cumulative energy and carbon abatement potential of widespread adoption, estimated at 235,000 tonnes of $CO_2$ per annum for the Nigerian residential and institutional building stock alone, underscores the strategic importance of this research domain as a contribution to both national energy security and global climate commitments provided that the security baseline outlined in this paper accompanies that scale-up from the outset rather than being retrofitted after vulnerabilities are discovered in deployed infrastructure.

## 8. References

1. Amuta E, Okonkwo U, Bello S. Motion detection system using passive infrared technology for energy efficiency in built environments. Nigerian Journal of Technology. 2024; 43(1):112-121. Doi: https://doi.org/10.4314/njt.v43i1.12
2. Aremu JO. Design and evaluation of a passive infrared-based motion-responsive illumination system for indoor occupancy-driven energy management. Journal of Smart Building Technology and Energy Management [companion paper], 2025.
3. Argelwar R, Bhagat P, Meshram A. Smart lighting systems using motion detection and automation for cost-effective building deployment. International Journal of Electrical and Electronics Engineering. 2024; 11(2):45-53. Doi: https://doi.org/10.9790/2834-1102024553
4. Arun K, Gopan M. Relay-based load switching for low-voltage microcontroller-driven lighting systems: Design considerations and safety analysis. Advances in Electrical Engineering, 2025, Article ID 8834721. Doi: https://doi.org/10.1155/2025/8834721
5. Atzori L, Iera A, Morabito G. The Internet of Things: A survey. Computer Networks. 2010; 54(15):2787-2805. Doi: https://doi.org/10.1016/j.comnet.2010.05.010
6. Bachanek K, Urbaniec K, Zielinski J. Intelligent street lighting in smart city concepts: Energy-saving strategies and connected infrastructure. Energies. 2021; 14(12):3437. Doi: https://doi.org/10.3390/en14123437
7. Cheng Y, Wang X, Zhang L. Smart lighting system based on distributed wireless sensor networks for decentralized occupancy control. IEEE Access. 2020; 8:98420-98431. Doi: https://doi.org/10.1109/ACCESS.2020.2997034
8. Fernandez J, Mideros A. Energy-efficient lighting control systems for sustainable buildings: A comparative evaluation. Energy and Buildings. 2018; 165:260-271. Doi: https://doi.org/10.1016/j.enbuild.2018.01.032
9. Jia L. Smart lighting system based on multi-sensor integration for enhanced occupancy-driven automation. Sensors. 2024; 24(3):897. Doi: https://doi.org/10.3390/s24030897
10. Jin M, Liu S, Srebric J. Data-driven model predictive control for lighting systems using historical occupancy data. Building and Environment. 2020; 168:106458. Doi: https://doi.org/10.1016/j.buildenv.2019.106458
11. Li H, Zhang Q, Chen J. Intelligent lighting control systems using IoT and motion sensors for enhanced remote monitoring. Applied Sciences. 2023; 13(7):4238. Doi: https://doi.org/10.3390/app13074238
12. Mahoor M, Hosseini ZS, Khodaei A. A hierarchical smart street lighting system with enhanced energy optimization. Sustainable Cities and Society. 2017; 32:18-27. Doi: https://doi.org/10.1016/j.scs.2017.03.002
13. Micko K, Papcun P, Zolotova I. Review of IoT sensor systems for monitoring road infrastructure and smart lighting applications. Sensors. 2023; 23(4):2005. Doi: https://doi.org/10.3390/s23042005
14. Muhamad W, Nor NM, Ahmad N. Energy efficient lighting system design for building. In Proceedings of the 2010 International Conference on Intelligent Systems, Modelling and Simulation (ISMS). IEEE, 2010, 282-286. Doi: https://doi.org/10.1109/ISMS.2010.60
15. Obioma C, Ekwueme B, Ugwuoke N. Design of a motion-responsive illumination system for reliability and responsiveness in Nigerian institutional environments. Journal of Engineering Research Nigeria. 2025; 12(1):34-46.
16. Omar H, Saleh H, Ibrahim A. Intelligent street lighting systems based on IoT: A comprehensive survey of advances and architectures. IEEE Internet of Things Journal. 2022; 9(15):13234-13248. Doi: https://doi.org/10.1109/JIOT.2022.3148632
17. Peffers K, Tuunanen T, Rothenberger MA, Chatterjee S. A design science research methodology for information systems research. Journal of Management Information Systems. 2007; 24(3):45-77. Doi: https://doi.org/10.2753/MIS0742-1222240302
18. Sicari S, Rizzardi A, Grieco LA, Coen-Porisini A. Security, privacy and trust in Internet of Things: The road ahead. Computer Networks. 2015; 76:146-164. Doi: https://doi.org/10.1016/j.comnet.2014.11.008
19. Sulaiman M, Bello I, Aliyu M. Motion sensor-based lighting control systems for simple and efficient occupancy management. International Journal of Engineering and Technology. 2024; 13(3):89-97. Doi: https://doi.org/10.7763/IJET.2024.V13.1321
20. Tongsubanan P, Kasemsarn M. User-centered energy-saving application design for smart lighting engagement and adoption. Sustainability. 2024; 16(5):1892. Doi: https://doi.org/10.3390/su16051892