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Pilot Study for Optimization Strategy for A Smart Monitoring and Alert Energy Consumption Ensemble: A Case of Enhanced Security

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ABSTRACT

There is today, a global shift caused by digital revolution for energy use efficiency, optimization, and consumption via its consequent adoption of sensor units for optimal-fit, and effective management solutions that will in turn – ripple across the society as its outcome, improved performance with reduced consumption as a new norm. Sensor-based units are eco-friendly with environ, consumption, health and regulation issues that replace traditional solutions with improved quality. We advance a sensor-design to observe societal condition associated with energy consumption in home appliance. It utilizes machine learning to analyze total energy consumed by each appliance and delivers optimal consumption that reduces energy waste. System as tested across multiple features to handle expansive input without delay or data losses – yielded the desired effectiveness, reliability, and efficiency; And affirm its performance stability even with more device connected.

1. INTRODUCTION

Governments globally, are overhauling their older system with smart-initiatives, with policy support and the required funding for smart grid deployment. By 2027, the global smart-grid asset market will have surpassed $125 billion the population explosion (Ojugo & Otakore, 2018; Zeineldin et al., 2013), the accelerated urbanization, and environmental policies enacted will all contribute as factors to heighten the fortunes as business strategies (Faheem et al., 2024; Ojugo et al., 2014). But, these advances have not the requisite policies and regulatory framework to support it exploitation. It ushers in technical, regulatory, economic, and consumer-behavioural issues that must be addressed for quick realization of intelligently optimized distribution (Ojugo, Akazue, et al., 2023; Shoaran et al., 2018). Thus, our smart distribution seeks to enhance conservation, efficiency, and sustainability. Energy optimization in residential settings have gained significant attention due to escalating energy costs and environmental concerns. A case in point is the complete overhaul with the budgeted ₦10-billion to ensure steady power and energy supply at the Aso-Villa in Abuja. But, residential buildings account for a large proportion of global energy consumption, yet inefficiencies such as energy waste and unmonitored appliance usage persist. The fusion of IoT offers a fit

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solution to these challenges, enabling real-time monitor, automation, and optimization of energy use (Ifioko et al., 2024). Smart energy monitors transmission and analysis of energy data via the use of advanced sensors to measure electrical parameters – while, exploring controllers like ESP32 to process the acquired data for further analysis (Krishna et al., 2023; Ojugo et al., 2021b). Thus, anomalies detection in energy-use can empower users with improved decisions on management to reduce energy waste with lowered cost (Muslikh et al., 2023; Yoro, Aghware, Akazue, et al., 2023; Yoro, Aghware, Malasowe, et al., 2023; Yoro & Ojugo, 2019b).

There is today, the rising trend that has birthed a genuine concern for energy consumption, health implication and its environmental impacts with the urgent call for replacement of traditional energy-conservation and power distribution systems with intelligent systems (Eboka, Odiakaose, et al., 2025; Grari et al., 2024) – due to the lack for realtime intelligent optimization and its requisite adaptability to effectively manage energy consumption. Smart grids have today (Jeong et al., 2023; Ojugo & Eboka, 2018) as business model promised solutions that seek to enhance the 2-way interaction of utilities (appliances) with consumers whom constantly seek to balance the consumption demands (Himeur et al., 2020; Odiakaose et al., 2025). With the aging infrastructure, distributed generation growth, increase engaged-users, and adoption of new innovations – there is now a great trend and shift for users to engage in the smart-meter initiative (Ako et al., 2024; Brizimor et al., 2024). With such advanced meters, energy distribution automation via innovative control and schemes have ushered in the self-monitor systems with controlled analysis for improved consumption (Ma et al., 2021; Tian, 2024). Smart energy systems have become an integral part of the smart grid that utilizes sensing, computation, and control that leans on users interaction with targeted user satisfaction (Atuduhor et al., 2024; Obasuyi et al., 2024) to advance efficient energy resources distribution with flexible load-shedding for improve reliability, cost and sustainability. Its core technologies integrated VAR control, fault detection isolation and restoration, advance smart metering, dynamic load-balance for energy management with predictive maintenance (Kizilkaya et al., 2022; Ojugo et al., 2021a; Ojugo, Ejeh, Odiakaose, et al., 2023).

This consequent adoption of embedded units has also continued to pose security risks to such data access and its accompanying integrity. The cyber-risks associated with such implementation cannot be overstated. This, often results in unauthorized (user) access and data breaches, which are identified as barriers that dissuade the fast adoption and adaptation of smart home initiatives (Ojugo, Aghware, et al., 2015; Sungheetha & Sharma R, 2020). To address these concerns, our proposed system will incorporates robust security measures via encrypted communication protocols for the ESP32, and secure user authentication protocols that will safeguard sensitive data – to yield a user-friendly and afford model that are critical and crucial to its widespread adoption (Ojugo, Eboka, et al., 2015; Ojugo, Ugboh, et al., 2013). Many existing systems are prohibitively expensive and complex, limiting their accessibility to average consumers. There is today, the growing need for low-cost and intuitive solutions to enhance user engagement and satisfaction (Okofu, Anazia, et al., 2024). Our proposed system leans on low-cost ESP32 and cloud-platform with optimization to address societal issues and contributes to sustainability via reduced overall energy demand with minimized residential carbon footprint (Aghware et al., 2023; Aghware, Adigwe, et al., 2024; Nguyen et al., 2024).

The study is motivated by the knowledge gaps (Geteloma et al., 2024a; Yoro & Ojugo, 2019a): (a) *inefficient Use:* Energy consumption in residential or home lacks proper and efficient monitoring to allow for effective management of energy resources

(Bhavani & Mangla, 2023; Ojugo, Ejeh, Akazue, et al., 2023). This leads to significant leakages. Many homes have no measure for the amount of energy consumed by each appliance(s) in their homes; Which results in energy wastage. Real-time monitor reduces consumption with an alert mode that helps to identify inefficiencies and blind-spot to optimize energy usage (Muhamada et al., 2024). The presence of granular monitor tools avail homes the capability to address such leakages effectively (Ali et al., 2024; Ojugo, Yoro, et al., 2015), (b) **IoT-Security:** IoT monitors are besieged with security vulnerabilities ranging from data storage modes (Pratama et al., 2025; Zuama et al., 2025) to communication protocols (Setiadi et al., 2025); Making them rife and susceptible to cyberattacks aimed at unauthorized access (Aghware, Ojugo, et al., 2024; Ugbotu et al., 2025). However, Singh et al. (2023) security concerns dissuade user adoption with IoT solutions due to risk of managing user sensitive data and consumption patterns as can be exploited by adversaries for malicious intents where not adequately protected (Ojugo & Oyemade, 2020; Oulhazzan et al., 2020), and (c) *High Costs and Complexity:* Existing energy monitors often explore high-costs, complex setups that deters widespread adoption among average consumers (Akazue, Okofu, et al., 2024; Malasowe, Edim, et al., 2024). But, Jebarani et al. (2020) have advanced that user-friendliness and cost are critical features for smooth and fast adoption of smart-homes as available units today – rely on expensive hardware and complex dynamic settings that renders it unaffordable to budget-conscious households. To curb this, we deploy targeted solution that balances affordability and function, and not herewith to compromise its performance (Mosavi & Bahmani, 2019; Nguyen et al., 2024).

The study hopes to (Akazue, Edje, et al., 2024): (a) design an IoT-based smart energy consumption ensemble with monitor and alert capabilities via an optimization strategy targeted at residential and home energy consumption (Ojugo & Yoro, 2021; Setiadi, Susanto, et al., 2024), (b) deploy the artifact via ESP32 microcontroller, (c) fuse a robust security mechanism to aid data transfer encryption and user authentication to protect system data and integrity, (d) deploy the proposed system on a cloud platform with user interface for real-time monitor, and (e) evaluate and benchmark the proposed system performance with existing solutions on metric such as throughput, efficiency, and cost (Ojugo, Ejeh, Akazue, et al., 2023; Yoro et al., 2025).

Our study contributes thus: Section 1 introduces subject with gaps, (b) Section 2 explores the proposed method – leaning on artifact design, implementation, and blockchain model with smart-contracts deployment, and (c) Section 3 – discusses obtained results as evidence.

2. MATERIALS AND METHODS

Our proposed IoT-based unit overcomes the gaps inherent with the qToggle system by Stolojescu et al. (Stolojescu-Crisan et al., 2021) – birthing features that enhance user convenience, energy efficiency, and scalability as a comprehensive solution fit for today's monitor and alert needs. It achieves this via its innovative solutions that leverages on enhance efficiency, scalability, and intelligence. Unlike the qToggle that relies on Wi-Fi, our proposed unit explores a hybrid comms protocol that integrates Wi-Fi with a low-power Zigbee (Geteloma et al., 2024b; Jo & Yoon, 2018) for enhanced encrypted communication between units to reduce consumed energy and improve scalability for larger residential setups. Also, system features cloud integration via the Google Firebase, which allows users access real-time (and historic) data remotely vis-à-vis aid adoption of a robust security measures using the encrypted data transmission cum multi-factor authentication scheme. Other key feats includes its boosted learning to optimize consumption at the various appliances as it explores predictive analytics to yield intelligent data insights (Aghware et al., 2025; Odiakaose et al., 2024) via detection of

energy-anomalies in consumption pattern (Binitie et al., 2024). Our proposed IoT-unit prioritizes modularity and interoperability via seamless fusion with the existing smart home devices. Its usage of the low-cost yet powerful ESP32-controller and sensors maintain affordability without compromising performance (Rawat et al., 2019; Saritha, 2020). In addition, it addresses the conflict of reliability and connectivity via a backup redundancy mechanisms and comms channel, to mitigate the impact of network disruptions (Rashid et al., 2021; Ye et al., 2021; Zekić-Sušac et al., 2021).

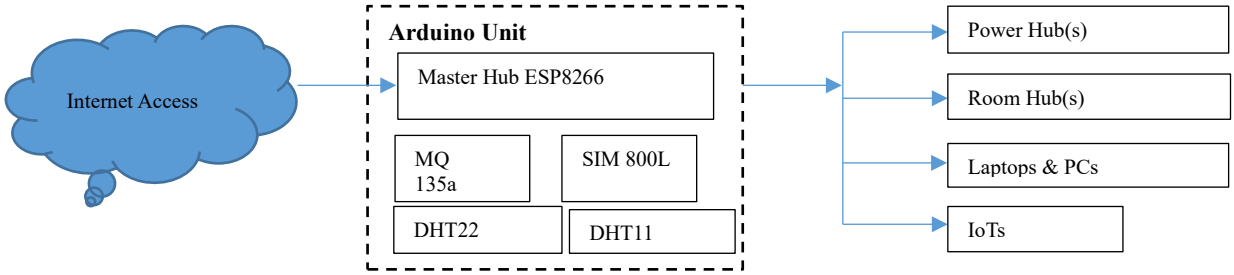

Figure 1. Proposed System Architecture

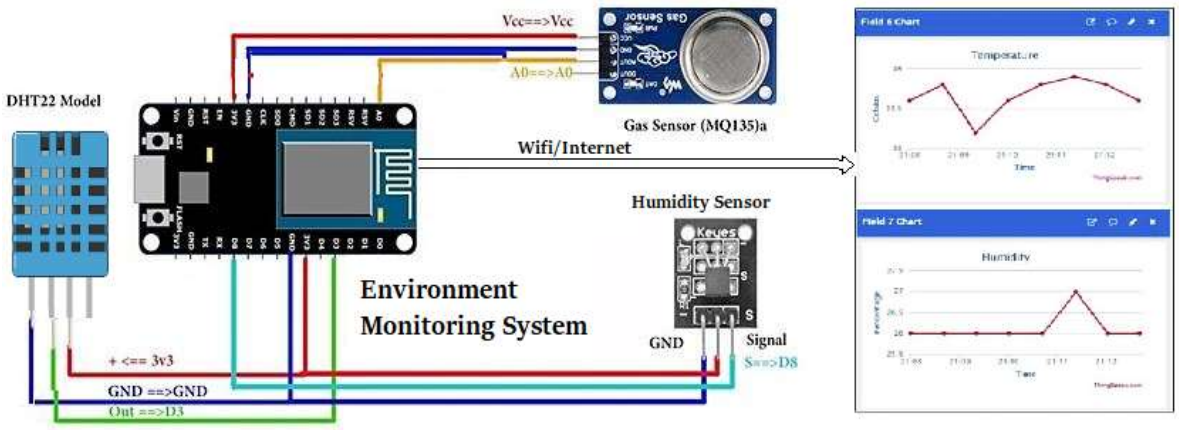

Figure 2. Circuit diagram of the Proposed System

Its circuit diagram as in Figure 2 – yield benefits for the architecture as thus:

1. Extended Realtime Processing: The unit offers full support for fast data acquisition and response, and handling multi-sensors simultaneously. Thus, improve real-time monitor and alert capabilities for timely decision-making in critical scenarios (Oladele et al., 2024; Omede et al., 2024; Oyemade et al., 2016).
2. Scalability: It yields extensive support for units expansion via the integration of newer and additional sensors/devices often required for both manual cum automatic configuration, increasing flexibility with reduced complexity for future upgrades (Sendra et al., 2020).
3. Improved Data Storage and Management: The proposed system adoption of cloud-platform allows for robust, long-term data storage, and efficient archival cum retrieval structure that yields improved historical data analysis and trend forecast (Onoma, Ugbotu, et al., 2025; Otorokpo et al., 2024).
4. Security: Its improved security protocol allows for enhanced data transfer capabilities with encrypted data mode that accounts for less susceptible and vulnerable access (Eboka, Aghware, et al., 2025; Onoma, Agboi, Geteloma, et al., 2025; Onoma, Agboi, Ugbotu, et al., 2025).
5. Intuitive User Interface for remote access (Ejeh et al., 2024; Ojugo, Yoro, Yerokun,

et al., 2013), with enhanced engagement and monitor capabilities across confined physical location (Ojugo & Eboka, 2020; Okpor et al., 2025).

With the system incorporating a diverse range of sensors like voltage, weather and tamper to yield a richer, heterogeneous data for improved situational intelligence (Setiadi, Muslikh, et al., 2024; Setiadi, Nugroho, et al., 2024) with other merits as: (a) use of multi-channel relay that offers real-time, policy-driven load control for higher grid response (Alqourabah et al., 2021; Putri & Faisal, 2023), (b) fused mode that supports localized data processing and learning execution on its gateway to yield quick, resilient knowledge, (c) widely-used protocols (DNP3, Modbus, WiFi and GSM) to seamlessly integrate with the legacy infrastructure and network (Ojugo & Eboka, 2019), (d) modular closure and its open-source customization for scalable needs (Okpor, Aghware, Akazue, Ojugo, et al., 2024), (e) wider adoption, and (f) complex dashboards and databases supplement real-time monitoring with retrospective analysis (Chen et al., 2020; Ojugo, Odiakaose, et al., 2023; Singh & Mantri, 2024).

This transforms the architecture into a fully operational prototype of the IoT-based monitor It selects, integrates, and programs both hardware and software components to align with the functional and performance requirements. At its nexus is the DHT11/DHT22 for temperature and humidity sensing, voltage and current sensors for electrical features tracking, and ESP32. Wireless comm facilitated via ESP8266 Wi-Fi and GSM SIM800L (for network availability and deployment scenarios). The units were interfaced on custom PCB with careful attention to pin-configure, regulated voltage, and grounding settings to ensure signal integrity and safety. We used Arduino IDE with embedded C/C++ for real-time sensor data acquisition, preprocessing (for data smoothing and calibration), and wireless data transmission. The unit included routines for error handling, packet formatting (JSON or URL encoding), and automated reconnection protocols in case of network failures. Additional logic was use to handle threshold-triggers like sending alerts if temperature or current exceeded predefined limits. These features ensure the system was not just a passive monitoring tool but also capable of proactive event management.

For cloud integration – we used Google Firebase to receive, store, and visualize transmitted data. ThingSpeak capability to visualize real-time graphs as widgets to display dynamic sensor data; while, Firebase offered alternate functions such as structured data storage with real-time synchronize for smartphone integration. Its user-friendly interface allowed for porting on both iOS and Android platforms (Okpor, Aghware, Akazue, Eboka, et al., 2024) – allowing users access to live data, review observed trends, and send control signals back to a device (Oyemade & Ojugo, 2020). Implementation was designed with modularity and scalability in mind. This meant that additional sensors or features such as GPS, motion detection, or camera modules could be easily added in the future without overhauling the system architecture.

The use of cloud platforms and APIs further enabled interoperability with third-party apps and services, opening pathways for future fusion with predictive anomaly detection (Safriandono et al., 2024). In overall, the implementation approach ensured a robust, flexible, and real-time IoT monitor solution suitable for diverse application domains such as smart homes, industrial automation, energy metering, and environmental monitoring.

3. RESULT FINDINGS & DISCUSSION

3.1. System Throughput

Throughput metrics evaluates how efficiently our proposed system processes and transmits data packets over network under varying operational loads (Eboka & Ojugo, 2020). This metric reflects the system's data handling capacity of the IoT – especially for cases of multi-connected sensors transmitting simultaneously as

detailed in Table 1. Results yields a consistent throughput rise with more devices connected to imply data transfer with peak throughput reached at 70-packets at the highest device load – to affirm suitability for real-time monitor and alert.

Table 1. Throughput Performance

Time	Throughput in packets per seconds
08:00	30
10:00	45
12:00	55
14:00	65
16:00	70

3.2. Performance Efficiency

Efficiency evaluates how optimally the system utilizes hardware resources like memory, CPU, and power during its operations cum processing (Malasowe et al., 2023; Malasowe, Okpako, et al., 2024). An efficient system maintains a consistent performance with minimal resource consumption as is critical for IoT environments where resources are limited. Table 2 details the performance whereas efficiency is based on system resource usage under different loads. Results showed the system consistently maintained high(er) efficiency with a slightly upward performance at peak operational hours, likely due to stable code optimization and efficient data handling mechanisms.

Table 2. Efficiency Performance

Time	Efficiency in Percentage
08:00	85
10:00	88
12:00	86
14:00	89
16:00	90

3.3. Scalability

Metric evaluates the total number of connected devices that the IoT can simultaneously handle without inherent performance degradation. It assesses if the system can maintain data integrity, responsiveness, and connectivity under expanding operational load as in Table 3.

Table 3. Scalability Performance

Time	Scalability in the connected devices
08:00	10
10:00	25
12:00	40
14:00	60
16:00	75

3.4. Discussion of Findings

Our system delivers promising results across multiple test parameters, to yield improved effectiveness, reliability, and efficiency. It affirms its capability to maintain a stable performance even with more device connected to the unit. Use of ThingSpeak is able to handle expansive inputs without delays or data losses. Its throughput demonstrated consistent and acceptable levels of performance even with the congested (simulated), maintained network scenario that yielded regular updates to the cloud platform with minimal packet loss(es) that ensures real-time visibility of monitored and alerted features (Malasowe, Aghware, et al., 2024). Its high-response to data capture and transfer demonstrates that consumption remained minimal due to low-power sensors for optimized power usage (Ehsan et al., 2022). This is crucial for real-world deployment, where battery efficiency and resource management are priorities. Its response time (between data sensing and cloud) achieved a milliseconds hit under multi-threaded input states (Nartey et al., 2021). Accuracy is validated via repeated trials and benchmarking – and use of the low-cost sensors with robust cloud-backend provisioned an efficient and scalable, responsive IoT with feedback. Results showed its deployment readiness (Jebarani* et al., 2020) and potential enhancements.

Our findings are discussed thus:

1. **Enhanced User Experience (UX):** Our mobile app offers comprehensive management capabilities with an easy-to-use, user-friendly graphic interface for all operations across diverse platforms (Sharma & Enbody, 2017). With an average load-time of 2.1 seconds, it yields optimized code architecture (Ojugo & Otakore, 2020) with efficient resource

utilization for rapid access to critical authentication mode. With a 99.8% synchronization over its blockchain for successive connectivity, this ensures robust communication protocols with maintained system functionality even in fault-prone, network-challenged conditions (Ojugo, Yoro, Oyemade, et al., 2013). User experience showed consistently high satisfaction scores that validate the app's design effectiveness. Its ease of use with average 4.7/5.0 rating implies its design minimizes training required while maximizing functional accessibility. Interface clarity of 4.8/5.0 rating shows a visual design with enhanced user comprehension. Feature accessibility with a 4.6/5.0 rating implies its critical functions are easily discoverable for varied UX-levels and technical competence (Agboi et al., 2025).

2. **Performance Optimization:** The ESP32 controller showed exceptional resource utilization efficiency throughout the extended operations tests and validated optimization strategies used in its design. Its usage averaged 23% at active authentication cycles – to yield a balanced, computational load distribution that maintains substantial processing headroom for additional functionality (Dhinakaran, 2023). Memory consumption stabilized at 180KB RAM usage, which represents 45% of available memory resources to ensure adequate buffer capacity for system stability and expansions (Kumar et al., 2019). Smart contract execution showed consistently high performance across varied network conditions and operational scenes, with average gas per authenticated transaction of 85,000 consumption. It implies a comprehensive functionality with cost-effective execution. With 15-transaction per second at peak usage periods, it demonstrates adequate capacity for high-demand scenarios while maintaining security verification integrity.
3. **Cost-Benefit Deploy:** Initial investment analysis revealed a 57% higher cost for blockchain compared to a conventional scheme, attributed to components and blockchain (Cha et al., 2018). Its operational benefits justify the added investment with improvements in security and administrative efficiency. The enhanced security resulted in fewer successful breaches compared to traditional systems, as substantial cost avoidance via reduced incident response, damage mitigation, and reputation protection requirements (Oyemade & Ojugo, 2021). Its deployment identified critical factors to facilitate its smooth implementation and operation effectiveness (Karanjai et al., 2023) with minimal training requirements, and comprehensive awareness as provisioned for the administrative staff to achieve operational competency in system management, user administration, and troubleshooting modes (Setiawan & Kerlooza, 2019). Integration test shows 95% compatibility with existing infrastructure systems, minimizing modification requirements and reducing implementation complexity for businesses with established access control (Ojugo & Yoro, 2020; Okofu, Akazue, et al., 2024).

4. CONCLUSION

Our system affirmed its viable, efficient solution for real-time data acquisition and remote system supervision. Its integration of microcontrollers, sensors and cloud tech allows for seamless fusion, integration and intelligent management to enhance monitor features. System is able to detect and transmit data autonomously with minimal human intervention. It yields high responsiveness accuracy, and underpins it as a transformative, smart IoT to foster automation, adapt to environmental regulations, and improves operational decision support. It provisions an adaptable, scalable model that can be tailored to various domains and scenarios.

Conflict of Interest

The authors declare that there is no conflict of interest.

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