

A Bio-Inspired Smart Home: AI-Driven Adaptive Energy Management with Edge Computing, Blockchain Security, and Self-Powered IoT Sensors

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Abstract. The evolution of smart home systems has emphasized energy efficiency, automation, and security; however, existing models often compromise user adaptability, real-time decision-making, and sustainability. This paper presents a bio-inspired, eco-smart home framework that integrates self-powered IoT sensors, edge computing, AI-driven adaptive interfaces, and blockchain-enhanced security to optimize energy management while maintaining occupant comfort. The proposed system employs triboelectric energy-harvesting sensors to reduce battery dependency, edge computing (NVIDIA Jetson Xavier NX, Raspberry Pi 4) to minimize latency, and AI-powered adaptive dashboards to personalize automation based on user behavior. Additionally, a blockchain-based authentication mechanism ensures secure data exchange between IoT devices, cloud infrastructure, and actuators. A prototype implementation and real-world evaluation demonstrate significant improvements in energy efficiency, responsiveness, and user engagement compared to traditional smart home systems. This research contributes a novel, sustainable, and intelligent architecture that redefines the future of self-learning, eco-friendly smart homes.

Keywords: Sustainable IoT Smart Home · Blockchain Security · Edge Computing · Adaptive User Experience · Triboelectric Sensors

1 Introduction

The rapid rise of Internet of Things (IoT) technologies has profoundly changed how we interact with our living environments, transforming passive structures into "smart homes" capable of dynamic control and feedback. For instance, buildings consume around 40% of the energy consumption globally, making the reduction of their ecological footprint [1]. In response, integrating remote sensing, Artificial Intelligence, and green energy systems is more important to develop more sustainable, innovative, more cost-effective and environmentally friendly smart homes [2, 3].

In addition, the advancement of smart homes is currently focusing on optimizing user experiences and customizing their needs and preferences. For instance, several studies

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O. Gervasi et al. (Eds.): ICCSA 2025 Workshops, LNCS 15895, pp. 129–141, 2026.
https://doi.org/10.1007/978-3-031-97651-3_9

have shown that technology adoption of smart homes are not only associated with technical aspects, but also with the user interaction, trust, usability and behaviour associated with this technology [4, 5]. This more socio-technical perspective has catalyzed for more interactive interfaces, accommodating users' habits, and comfort [3, 6]. Consequently, the concept of "smart living" extends automation to adaptive environments that learn from and respond to user behaviors, ensuring higher user satisfaction and acceptance of this IoT application [7, 8].

In order to achieve high adaptability, edge computing is considered an important backbone for smart home operations, to avoid latency in response time and security issues with user information [9, 10]. In addition, the development of triboelectric and self-powered sensors has improved the hardware capabilities; in increasing their sensing ability to harvest ambient energy from everyday movements [5, 8]. These collective advances have facilitated the fully autonomous and sustainable home systems.

However, there are challenges regarding the balance between the bio-sustainability, usability, and cyber privacy and security [6, 10]. Some technological attempts can optimize energy savings, for instance, at the cost of user-friendliness or system security, and vice-versa, which can result in misusing important features and options [4]. Moreover, data security and privacy concerns, if frequently surface, can negatively impact user trust in smart homes [11]. Therefore, a human-centered approach should be considered when developing the technological framework of any IoT smart home, and thus, this research proposes a bio-inspired smart home framework, in an attempt to addresses these challenges by ensuring a balance between energy sustainability, privacy and security, and usability.

Our proposed framework proposes a state-of-the-art smart home architecture that combines sustainable and eco-friendly IoT infrastructure with adaptive user experience aspects to achieve a genuine green and user-accepted living environment. Drawing on existing research [6, 8, 11, 12], we aim to bridge gaps between machine learning-based energy optimization, triboelectric sensor technologies, edge computing, and occupant-centric design. By uniting these elements in a single cohesive framework, this study endeavors to lay a foundation for intelligent, resource-efficient, and truly occupant-responsive smart homes of the future.

The rest of the paper is organized as follows: a literature review presents existing research and identifies key gaps, followed by a methodology detailing our smart home design approach. This is then complemented by a discussion of the findings, implications, limitations, and directions for future work.

2 Literature Review

Smart home research has progressed significantly over the past decade, transitioning from basic automation systems to sophisticated IoT-driven environments aimed at improving both sustainability and occupant well-being. Early studies established the importance of building energy management, highlighting how real-time data collection and control could drastically reduce consumption and costs [1, 2]. This foundational work paved the way for broader discussions on system architectures that integrate intelligent computing, renewable energy sources, and occupant comfort [7, 10, 11].

A prominent theme within these discussions is user-centered design, reflecting the notion that technology adoption hinges on comprehensibility and meaningful benefit. Mao and Chang [3] emphasize that cross-device interaction is frequently overlooked, impeding smooth digital transformation in domestic contexts. Jakobi et al. [4] reveal how user confusion in living lab environments can derail intended system efficiency, while subsequent longitudinal research underscores a rising demand for intelligibility and accountability in everyday IoT usage [12]. Similarly, the work [6, 13] demonstrates how comfort encompasses not just temperature but also overall user experience—suggesting that next-generation smart homes should account for emotional and psychological factors. Other scholars [14] further argue that applying affordance theory ensures intuitive interfaces, strengthening overall user acceptance.

Parallel to these user-focused investigations, a substantial body of research addresses big data and machine learning as catalysts for energy optimization. Machorro-Cano et al. present HEMS-IoT, a platform harnessing large datasets to refine energy use in near real time [6]. Incorporating machine learning into smart home frameworks, these studies show how predictive models can facilitate dynamic scheduling of appliances or integration of renewable energy. Sepasgozar et al. [14] corroborate this through a systematic review of AI and IoT applications, concluding that while these technologies can significantly improve resource management, their impact on household behavior remains inconsistent without well-designed user engagement strategies.

Increasingly, researchers also explore advanced materials and self-powered sensors. The study [15] discusses sustainable triboelectric materials that transform mechanical energy (e.g., footsteps, door movements) into usable electrical signals. Shi et al. [16] extend these insights by focusing on flexible wood-based triboelectric technologies, enabling homes to derive ambient energy from daily activities. Though promising, these innovations highlight a challenge: bridging cutting-edge sensor technology with overarching system architectures that are both ecologically sound and easy for non-experts to maintain.

Discussions around architecture and edge computing underscore the importance of adaptable frameworks. Also, the researchers in [17] show how edge computing can alleviate cloud-based bottlenecks, ensuring faster decision-making for energy management. Likewise, the study [18] traces the evolution from self-powered sensors to AIoT ecosystems, suggesting that decentralized architectures empower households with real-time analytics. However, most such models do not fully embrace occupant-centric design principles, indicating an opportunity to combine robust edge solutions with intuitive, adaptive interfaces [19].

Within the sustainability domain, numerous scholars propose robust methods for lowering carbon footprints and optimizing renewable integrations. Rehman et al. [7] investigate demand response in tandem with renewable sources, showcasing how grid stability and cost reduction are mutually achievable goals. Sodhro et al. [13] push for optimal resource management to achieve green and sustainable smart cities, arguing that homes represent the fundamental building blocks of broader urban systems. AlGhenaim and Hamdan [11] examine how well-designed optimization strategies not only reduce environmental impact but also improve overall quality of life. In this context, He et al.

[10] position IoT-based, green-centric solutions as pivotal for next-generation urban planning.

Another key research direction examines adaptive home environments through personalized systems designed for diverse user demographics. For example, Goessler and Kaluarachchi [9] demonstrate how adaptive solutions can enhance spatial efficiency, while Keyanfar et al. [17] propose psychologically intelligent systems that address both functional needs and emotional well-being. Additionally, Lu et al. [18] illustrate how smart homes tailored for elderly populations can provide safety measures and improve quality of life for older adults.

Security and transparency, however, emerge as primary concerns in open IoT architectures. To address these concerns, Singh et al. [15] propose a blockchain-based approach to mitigate vulnerabilities and protect data against breaches, attacks and illegal penetrations. In addition, Jakobi et al. [12] indicate that users have significant concerns regarding data privacy in smart homes, and that technology acceptance and usage may decrease when users perceive low levels of personal data transparency.

The need to utilize the capabilities of big data analytics for designing user-friendly graphical interfaces for energy savings is considered crucial, especially in the choice of IoT services, multi-sensor technologies, and user-interaction applications. Whereas some studies prioritize advanced hardware solutions for self-powering or data collection [5, 16, 20] others concentrate on the algorithmic and interface aspects that shape day-to-day interactions [3, 4, 12, 21, 23]. Similarly, a few researchers delve deeply into macro-level sustainability frameworks [7, 11, 13], while others explore micro-level user experiences and emotional well-being [9, 17–20, 22–24].

In summary, extant literature confirms the enormous potential of AIoT-driven, adaptive, and eco-friendly architectures in modern smart homes. Yet, implementations often remain siloed—optimizing one domain (e.g., sensor innovation) without fully accounting for occupant behavior, security, or the interplay between multiple subsystems. This reveals a notable knowledge gap: an integrative design that synthesizes green IoT infrastructure, advanced materials, machine learning intelligence, and genuinely adaptive user experiences within a single cohesive framework is still lacking. By developing a holistic smart home architecture that unites these elements—alongside robust edge computing, comprehensive user-centric interfaces, and transparent governance—future research can push the boundaries of both environmental sustainability and human comfort. This study aims to address precisely that gap, presenting a state-of-the-art blueprint for achieving a more sustainable, green, and adaptive smart home system.

3 Methodology

The proposed smart home architecture is built upon a layered framework that integrates green IoT infrastructure, edge computing, and adaptive user interfaces to create an environment that is both sustainable and occupant-responsive. Our design approach is iterative and user-centric, drawing on insights from the literature to ensure a harmonious balance between energy efficiency, environmental sustainability, and user comfort [1, 21].

At the core of the architecture lies a multi-layered system that consists of a physical device layer, an edge computing layer, and a central control layer. The device layer

encompasses various IoT sensors; including sustainable, self-powered triboelectric sensors that harvest ambient energy [5, 16] to continuously monitor environmental conditions and energy usage. These sensors feed real-time data to the edge computing layer, where preliminary processing, aggregation, and machine learning-based analytics are applied for prompt decision-making and energy optimization [6].

As mentioned earlier, the edge computing layer is important to reduce latency and to improve system responsiveness [1, 2]. In details, the smart home system processes sensor data in real time using intelligent algorithms, automatically modifying energy distribution, anticipating any problems before they arise, and altering temperature and lighting according to user preferences and environmental factors. This mechanism supports both performance and environmental goals by increasing efficiency and lowering energy usage by processing data locally rather than depending on cloud servers.

A key aspect of our design is the adaptive, user-centric interface. Leveraging principles of affordance and cross-device interaction [3, 4, 21–25], the interface offers intuitive dashboards that display real-time energy consumption, ambient conditions, and system performance. It provides personalized recommendations and allows for both automated control and manual adjustments, ensuring that users remain in command while benefiting from intelligent optimizations that enhance their comfort and overall experience.

An interface that changes to meet the needs of users is the main goal of our design. It has user-friendly dashboards that provide the following information: Current energy use, room conditions (such as temperature), and system performance, all of which are based on established interaction concepts [3, 4, 21]. Users can select between manual control and automatic changes, and the system provides tailored advice. This maximizes comfort with clever optimizations while keeping consumers in control.

As data travels from sensors to the main hub, this bio smart home system employs cutting-edge security measures like blockchain verification [15] to protect it. This maintains operational transparency while safeguarding privacy. Additionally, its modular architecture makes it simple to integrate with other smart home appliances, ensuring that it will continue to work as technology advances.

Finally, our implementation strategy involves prototyping the entire system in a controlled laboratory environment, followed by real-world field trials. Evaluation metrics will focus on energy efficiency, system responsiveness, user satisfaction, and sustainability impact. Continuous user feedback and iterative testing will guide refinements, ensuring that the final design not only meets but exceeds the dual demands of ecological responsibility and user-centric performance. Figure 1 shows the proposed Eco-Smart home system through the multiple layers.

The architecture of the proposed eco smart home solution is designed to seamlessly integrate hardware components, advanced software systems, communication networks, and robust security protocols to create an energy-efficient, adaptive, and user-centric living environment. At its core, the system leverages a multi-layered architecture comprising IoT sensors, edge computing units, cloud-based analytics, adaptive user interfaces, and smart home actuators. This layered approach optimizes performance, enhances data security, and ensures real-time responsiveness while minimizing energy consumption.

The hardware components include a variety of IoT sensors strategically placed throughout the home to monitor environmental conditions, energy usage, occupancy,

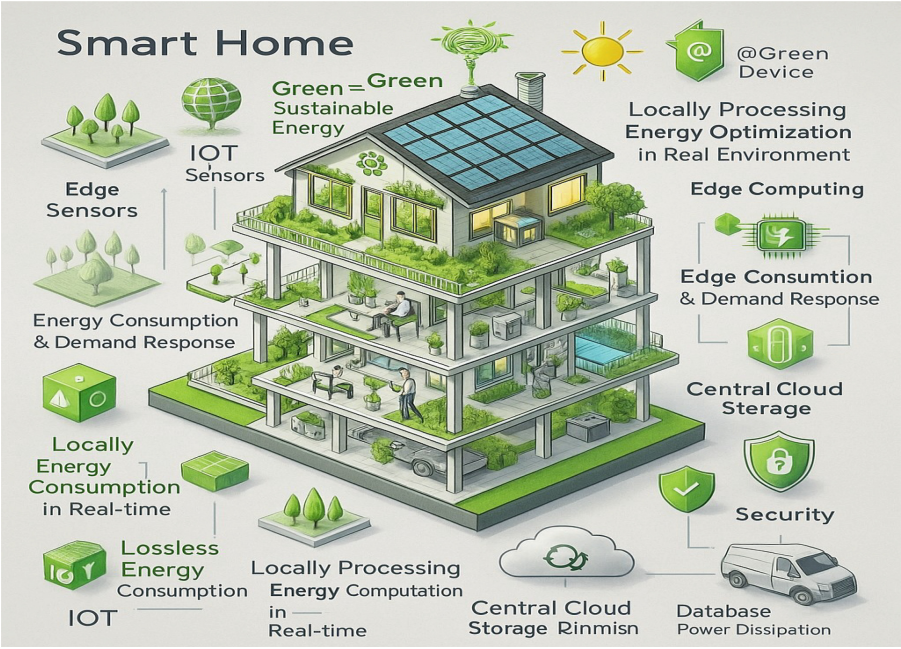

Fig. 1. Holistic overview of the layered smart home (Generated by ChatGPT 4.0)

and user behaviors. These sensors encompass triboelectric self-powered sensors, which harvest energy from ambient movements like walking, reducing battery dependency and enhancing sustainability.

In addition, and in order to enable intelligent automation, the system makes use of sensors, such as motion detectors, temperature, and humidity sensors. It uses Zigbee and Z-Wave protocols to wirelessly operate lights, HVAC controllers, and appliances while maintaining device compatibility. It combines solar panels with intelligent battery storage for energy efficiency, lowering reliance on the grid and promoting sustainability.

Using a Raspberry Pi 4 for simpler operations and an NVIDIA Jetson Xavier NX for more complicated processing, the edge computing devices act as the local brain of the system. Machine learning algorithms are used by these devices to predict energy use, optimize device scheduling, and automatically modify environmental settings. The system reacts more quickly, uses less bandwidth, and is more efficient when data is processed locally rather than in the cloud. IoT-optimized MQTT (Message Queuing Telemetry Transport) and CoAP (Constrained Application Protocol) protocols ensure that all communication with the cloud layer is safe.

Both the AWS and Azure cloud platforms are used by the cloud control layer in the proposed Bio smart home, which combines their advantages to store data for a long time, examine trends, and enhance intelligent algorithms. Using cutting-edge AI (RNNs and GBMs), it gathers data from all of the edge devices in your house to forecast your requirements and provide tailored recommendations. This solution allows you to safely

monitor or manage your house from any location. Blockchain verification and military-grade encryption (TLS 1.3) guard against tampering with any data that moves between your devices and the cloud.

In addition, the suggested solution keeps all of your devices linked quickly and securely by utilizing a smart mesh network that combines Wi-Fi 6 and Thread. Data can be accessed only through blockchain verification and bank-level encryption (AES-256). Powered by Node.js/Express.js in the background, the user-friendly dashboard (created using Vue.js) displays the energy usage in real time, the home environment, and personalized suggestions. With its modular design, robust infrastructure, and state-of-the-art components, this eco-smart home solution ensures a high-performance, secure, and sustainable living environment tailored to modern user needs.

To validate the proposed architecture, we conducted a series of experiments in a controlled laboratory environment, followed by real-world field trials in a smart home prototype. The prototype was equipped with IoT sensors, edge computing units, a cloud control layer, an adaptive user interface, actuators, and renewable energy integration. Triboelectric self-powered sensors, environmental sensors (temperature, humidity, CO_2), and motion detectors were deployed throughout the home to monitor energy usage, environmental conditions, and user behavior. Edge computing units, powered by NVIDIA Jetson Xavier NX and Raspberry Pi 4, were used for local data processing, running machine learning algorithms to optimize energy consumption and environmental controls. The cloud control layer, hosted on AWS IoT Core and Microsoft Azure IoT Hub, aggregated data from multiple edge devices, enabling predictive analytics and personalized recommendations. The user interface, developed using Vue.js for the frontend and Node.js with Express.js for the backend, provided adaptive dashboards that displayed real-time energy consumption, environmental conditions, and personalized recommendations. Actuators, including smart lighting, HVAC controls, and appliance controllers, were integrated using Zigbee 3.0 and Z-Wave Plus standards, ensuring reliable wireless communication and interoperability with third-party devices. Solar panels connected to a smart energy management system and lithium-ion battery storage were used to enable sustainable energy utilization and grid independence.

The following Table 1 summarizes the Key Components of the proposed smart home infrastructure.

It is noteworthy that the selection of NVIDIA Jetson Xavier NX as the edge computing unit is based on its optimal balance between computational power, energy efficiency, and cost-effectiveness. Unlike Intel Movidius, which is optimized for lightweight AI inference tasks, Jetson Xavier NX provides higher processing power (21 TOPS AI performance), better GPU acceleration, and enhanced real-time data handling, making it more suitable for latency-sensitive smart home automation tasks. Its ability to execute deep learning models on-device minimizes reliance on cloud processing, reducing latency and network dependency.

Similarly, AWS IoT Core was chosen over private cloud alternatives due to its scalability, real-time device communication, and seamless integration with edge computing frameworks. AWS IoT Core offers low-latency MQTT-based messaging, serverless computing via AWS Lambda, and robust device authentication and encryption, ensuring secure and efficient data exchange between edge devices, cloud services, and actuators.

Table 1. List of Eco-Smart Home infrastructural component.

Component	Description
User Devices	Smartphone, Tablet, Laptop—Interfaces with the smart home system via web/app
IoT Sensors	Triboelectric, Environmental, Motion Sensors – Collect real-time data on energy, security, and climate conditions
Edge Computing	NVIDIA Jetson Xavier NX, Raspberry Pi 4 – Local processing using ML for energy optimization
Smart Home Actuators	HVAC, Lighting, Security, Appliances – Adjusts environmental settings based on AI-driven optimization
Cloud Control Layer	AWS IoT Core, Microsoft Azure IoT Hub – Stores and analyzes system data, supports AI model refinement
Database & Storage	PostgreSQL, Cloud Storage – Manages historical data, logs, and ML model updates
Communication Network	Wi-Fi 6, Zigbee, Z-Wave, MQTT – Secure wireless protocols for device connectivity
Security Layer	Blockchain authentication, TLS 1.3 encryption – Ensures secure and private data transmission

Its multi-region support enhances system redundancy and fault tolerance, making it ideal for real-time smart home operations that demand both performance and reliability.

Moreover, integrating blockchain-based security mechanisms into smart home systems presents a trade-off between performance and security. On the security side, blockchain ensures tamper-proof data integrity, decentralized authentication, and immutable logs, effectively mitigating risks associated with IoT device spoofing, unauthorized access, and data manipulation. Additionally, its smart contract-based automation enables trustless execution of device commands, enhancing transparency and reducing the reliance on centralized authorities. The table precisely aligns with your research focus on IoT-driven energy optimization, edge computing, security, and adaptive smart home automation. The architectural design of the components is shown in the deployment model below (Fig. 2).

The system should be tested under various scenarios, including peak energy demand, low occupancy, and extreme weather conditions. Key performance metrics such as energy efficiency, system responsiveness, user satisfaction, and sustainability impact were measured. Continuous user feedback was collected to refine the system iteratively, ensuring that it met the dual demands of ecological responsibility and user-centric performance.

In order to illustrate the interaction and data flow within the smart home system, detailing how key components mentioned earlier, a UML-sequence diagram is modelled for the purpose of this proposed smart home, representing the process of collecting sensor data, processing it locally, sending it to the cloud for analytics, making decisions, executing actions, and refining system performance through a feedback loop. This diagram (shown in Fig. 3) provides a structured visualization of the system's operation, ensuring

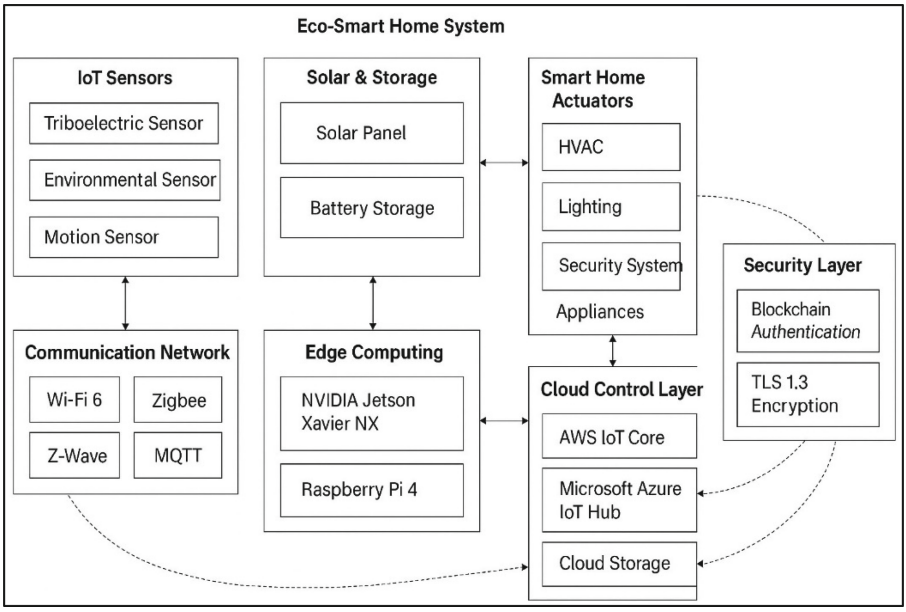

Fig. 2. Deployment model of the proposed Eco-Smart Home

efficiency, scalability, and real-time responsiveness among the main components of the proposed Eco-smart system.

The eco-smart home interface is an intelligent, centralized control system that integrates energy management, environmental monitoring, security automation, and AI-driven recommendations into a seamless, interactive dashboard. It enables users to optimize energy consumption, adjust smart devices, and monitor real-time data from IoT sensors and edge computing. Designed for accessibility and mobility, the interface supports remote control via tablets and smartphones, ensuring a responsive, AI-powered, and sustainable smart home experience that enhances both comfort and energy efficiency. The interface prototype is show in Fig. 4.

The smart home control panel interface is designed as a centralized, highly interactive dashboard that provides users with real-time insights into energy consumption, environmental monitoring, security, and automation controls. The interface features a modular design, where key functions such as eco-mode activation, smart lighting and HVAC control, security feeds, and AI-driven sustainability recommendations are presented through dynamic dashboards. Users can seamlessly interact with the system using touch controls, sliders, and AI-assisted automation, ensuring a user-friendly and intuitive experience.

Also, sensors, edge computers, the cloud, and smart devices are all seamlessly connected by the system, enabling rapid and effective collaboration amongst all components. The user-friendly interface, which is compatible with all devices (phones, tablets, and wall panels), is a crucial component that enables remote home control. It even helps you save energy in real time with augmented reality displays and AI suggestions.

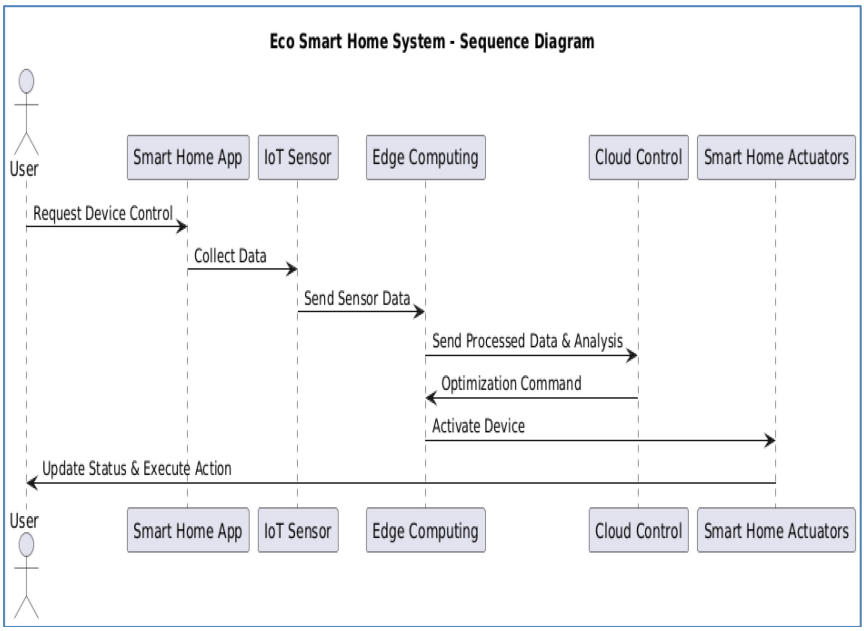

Fig. 3. Sequence Diagram of the proposed Smart home system



Fig. 4. Eco-Smart Home User Interface

Built with fast-updating protocols (MQTT/CoAP) and modern web technology (Vue.js frontend, Node.js/Express.js backend), it also functions flawlessly on mobile devices (Flutter/React Native) and maintains a secure cloud connection (AWS IoT Core/Firebase). This combination of smart automation, multi-device access, and instant data makes it a truly advanced yet user-friendly smart home solution.

4 Discussion

By integrating eco-friendly technology, quicker local processing (edge computing), and user-friendly controls into a single smart package, our smart home solution outperforms previous models. Our system processes data locally for immediate energy savings, in contrast to cloud-based solutions that may be delayed (such as in the model found in [1, 2]). In addition, our solution addresses the user-friendly issues brought up by [4, 19], and offers individualized advice and straightforward controls that genuinely function for users, in contrast to many systems that save energy but disregard comfort. Thus, it can be considered as a comprehensive improvement that keeps smart homes efficient while conserving electricity.

The incorporation of renewable energy sources and triboelectric self-powered sensors is consistent with the work of Wei et al. [5] and Shi et al. [16], whose research supports energy harvesting technologies and sustainable materials. However, our system goes further by combining these innovations with machine learning-based energy optimization, resulting in a more holistic approach to sustainability. The use of blockchain-based verification mechanisms and end-to-end encryption addresses the security concerns raised by Singh et al. [15] and Jakobi et al. [12], ensuring data integrity and user privacy, which are critical for gaining user trust.

Our architecture introduces several novel contributions. Unlike previous works that focus on individual components (e.g., sensors, edge computing, or user interfaces), our system integrates all these elements into a single, cohesive framework, ensuring a balance between energy efficiency, user comfort, and sustainability. The adaptive user experience is another key innovation, as the system learns from user behavior and provides personalized recommendations, ensuring a seamless and intuitive user experience. Additionally, the use of triboelectric self-powered sensors reduces battery dependency and enhances the sustainability of the system, a feature not commonly found in existing smart home solutions.

5 Limitations and Future Work

Despite these advancements, our system has some limitations. Scalability is a concern, as the system performs well in a single-home environment but may require further optimization for larger residential complexes or urban areas. The initial setup cost, including advanced sensors, edge computing units, and renewable energy systems, may also be prohibitive for some users. Furthermore, despite the intuitive interface, some users may still face challenges in adapting to the new technology, particularly older adults or those with limited technical expertise.

Future work should focus on addressing these limitations. Scalability improvements could optimize the system for larger-scale deployments, such as multi-family housing or smart cities. Exploring cost-effective alternatives for sensors and edge computing units could make the system more accessible to a broader audience. Developing user training programs and tutorials could help improve adoption rates, particularly among non-technical users. Additionally, further research could explore integrating the system with smart grids to enable bidirectional energy flow and enhance grid stability.

6 Conclusion

In conclusion, this study presents a state-of-the-art smart home architecture that integrates green IoT infrastructure, edge computing, and adaptive user interfaces to create a sustainable, energy-efficient, and occupant-responsive living environment. By combining advanced technologies such as triboelectric self-powered sensors, machine learning-based energy optimization, and blockchain-secured data transmission, the proposed system addresses key challenges in energy management, user comfort, and cybersecurity, while the adaptive user interface ensures a seamless and intuitive experience. Despite its limitations, including scalability challenges and initial setup costs, this holistic approach bridges the gap between environmental sustainability and user-centric design, offering a blueprint for future smart home systems. Future work should focus on optimizing the system for larger-scale deployments, reducing costs, improving user adoption through training programs, and integrating with smart grids to enhance sustainability and grid stability, ultimately paving the way for more intelligent, eco-friendly, and user-accepted living environments in the era of IoT and AI-driven innovation.

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